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REVIEW OF TRANSPORTATION FUEL LIFE CYCLE ANALYSIS

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The objective of this study is to provide an assessment of existing life cycle analyses of transportation fuels, including a review of methodologies, analytical tools and models. This project scope includes identifying gaps in existing methodologies, data tools and models, and comparing their assumptions and limitations. This study reviews the published studies which have received the greatest policy attention. The underlying models, documentation and related papers, and input assumptions are also examined.

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Terms and Abbreviations

AB32	California's Assembly Bill (AB) 32
ADL	Arthur D. Little, Inc.
ADVISOR	NREL's ADvanced Vehicle SimulatOR model
AERI	Alberta Energy Research Institute
AEZ	Agro-Economic Zone
AFLOU	Agriculture Forestry and Other Land Use
ALCA	Attributional Life Cycle Analysis
ANL	Argonne National Laboratory
ARB	California Air Resources Board
B100	Diesel fuel comprised of biodiesel alone (100% BD)
BC	Black Carbon
BD	Biodiesel
BESS	Biofuel Energy Systems Simulator model
BEV	Battery Electric Vehicle
C	Carbon
CA	California
CA-GREET	The standard GREET model modified for use under CA LCFS
CANDU	CANada Deuterium Uranium type nuclear reactor
CANMET	CANada Centre for Mineral and Energy Technology
CARBOB	CAlifornia Reformulated gasoline Blendstock for Oxygenate Blending
CARD	The FAPRI Center for Agricultural and Rural Development
CCGT	Combined Cycle Gas Turbine
CEC	The California Energy Commission
CEF	Carbon dioxide Equivalence Factor
CEI	Cost-Effectiveness Index
CENTURY	CENTURY Soil Organic Model
CETC	CANMET Energy Technology Centre
CGE	Computable General Equilibrium
CGF	Corn Gluten Feed
CGM	Corn Gluten Meal
CH_4	Methane
CI	Carbon intensity
CLCA	Consequential Life Cycle Analysis
CNG	Compressed Natural Gas vehicle fuel
CO	Carbon monoxide
CO_2	Carbon dioxide
CRP	Conservation Reserve Program
CONCAWE	CONservation of Clean Air and Water in Europe.
DAYCENT	A daily version of the CENTURY LCA model
DICEV	Direct Injection Combustion Engine Vehicle

DICI	Direct Injection Compression Ignition
DISI	Direct Injection Spark Ignition
DDGS	Dry Distiller's Grains and Solubles
DGS	Distiller's Grains and Solubles
dLUC	Direct Land Use Change
DOE	U.S. Department of Energy
DWT	Dead Weight Tonnage
E100	100% fuel ethanol
EDI	Economic Damage Index
EDIP97	An LCA model incorporating Environmental Design of Industrial Products
EER	Energy Economy Ratio
EF	Emission Factor
eGRID	Emissions and Generation Resource Integrated Database
EIR	Environmental Impact Report
EIA	Energy Information Agency, DOE
EISA	The Energy Independence and Security Act
EMPA	Eidgenössische Materialprüfungs- und Forschungsanstalt, the Swiss Federal Laboratories for Materials Testing and Research
EPA	U.S. Environmental Protection Agency
EPACT	Energy Policy Act of 2005
EPPA	Emissions Prediction and Policy Analysis model, MIT
EU	European Union
EUCAR	European Council for Automotive R&D
FAEE	Fatty Acid Ethyl Ester
FAME	Fatty Acid Methyl Ester
FAPRI	The Food and Agricultural Research Institute model; Iowa State University's Center for Agricultural and Rural Development
FAO	The Food and Agricultural Organization of the United Nations
FASOM	Forest and Agricultural Sector Optimization Model
FCV	Fuel Cell Vehicle
FFV	Flexible Fuel Vehicle
FQD	Fuel Quality Directive
FT	Fischer-Tropsch
g CO_2e/MJ	Grams of carbon dioxide equivalents per MJ of fuel energy produced
GE	General Equilibrium
GFCL	Gross Forest Cover Loss
GHG	Greenhouse Gas
GHGenius	An LCA model based on LEM that was developed for Natural Resources Canada
GM	General Motors
GREET	The Greenhouse gas, Regulated Emissions, and Energy use in Transportation model
GTAP	Global Trade Analysis Project model

GUI	Graphical User Interface
GWI	Global Warming Intensity
GWP	Global Warming Potential
HC	Hydrocarbon
HEV	Hybrid Electric Vehicle
ICEV	Internal Combustion Engine Vehicle
IFEU	Institut für Energie- und Umweltforschung Heidelberg
IFPRI	International Food Policy Research Institute
iLUC	Indirect Land Use Change or Indirect Land Use Conversion
IPCC	Intergovernmental Panel on Climate Change
ISOR	Initial Statement of Reasons
JEC	JRC/EUCAR/CONCAWE
ISO	International Standards Organization
JRC	Joint Research Centre
K	Potassium
LBST	Ludwig Bölkow Systemtechnik
LCA	Life Cycle Analysis or Life Cycle Assessment
LCFS	Low Carbon Fuel Standard
LCI	Life Cycle Inventory
LDV	Light-Duty Vehicle
LEM	Lifecycle Emissions Model
LNG	Liquefied Natural Gas
LP	Linear Programming
LPG	Liquefied Petroleum Gas
LUC	Land Use Change or Land Use Conversion
MIT	Massachusetts Institute of Technology
MODIS	Moderate Resolution Imaging Spectrora diameter (a Satellite Tool)
MSW	Municipal Solid Waste
N	Nitrogen
N_2O	Nitrous oxide
NASS	National Agricultural Statistics Service
NE	Northeast
NEMS	National Energy Modeling System
NESCAUM	Northeast States Coalition for Coordinated Air Use Management
NERD	Non-Ester Renewable Diesel
NETL	National Energy Technology Laboratory
NG	Natural Gas
NMOC	Non-Methane Organic Compound
NO_x	Oxides of nitrogen
NREL	National Renewable Energy Laboratory
O_3	Ozone
OM	Organic Matter

P	Phosphorus
PAS	Publicly Available Specification
PE	Partial Equilibrium
PEM	Proton Exchange Membrane
PHEV	Plug-In Hybrid Electric Vehicle
PISI	Port Injection Spark Ignition
PSAT	Powertrain System Analysis Toolkit model
RD	Renewable Diesel
RED	Renewable Energy Directive
REDD	Reducing Emissions from Deforestation and Forest Degradation
RIA	Regulatory Impact Assessment
RFA	Renewable Fuels Association
RFS2	Revised Federal Renewable Fuels Standard
RIA	Regulatory Impact Analysis
RPS	California's Renewable Portfolio Standard
RSB	Roundtable on Sustainable Biofuels
RTFO	Renewable Transportation Fuel Obligation
SBM	Soy Bean Meal
SCR	Selective Catalytic Reduction
SI	Système International d'unités, the International System of Units
SO_2	Sulfur dioxide
SOA	Secondary Organic Aerosols
SOC	Soil Organic Carbon
SO_x	Sulfur Oxides
T&D	Transport and Distribution
TTW	Tank-To-Wheel
UC	University of California
UCD	University of California, Davis
UK	United Kingdom
ULSD	Ultra Low Sulfur Diesel
UN	United Nations
UNL	University of Nebraska, Lincoln
USDA	U.S. Department of Agriculture
VOC	Volatile Organic Compounds
WTT	Well-To-Tank
WTW	Well-To-Wheels

Summary

Background

The 2007 Energy Independence and Security Act (EISA) requires that at least 36 billion gallons of renewable transportation fuels be used annually in the U.S. by 2022. Various types of renewable fuels used to fulfill this requirement must achieve greenhouse gas (GHG) emission reductions relative to conventional gasoline and diesel fuel sold in 2005. GHG emissions are determined on a life cycle-basis, including direct and significant indirect emissions related to the full fuel life cycle from feedstock generation or extraction, through the distribution, delivery, and use of the fuel by the final consumer.

In addition, California's Low Carbon Fuel Standard (LCFS) requires a 10% reduction in the carbon intensity of gasoline and diesel in the state by 2020, with potential further reduction targets through 2050. The European Commission also established a Renewable Energy Directive, which requires 10% renewable fuel with a 35% GHG reduction target. Other initiatives include the Renewable Transportation Fuels Obligation (RTFO) in the United Kingdom (UK) and various LCFS program proposals being considered in the U.S., all of which require assessment of transportation fuel GHG emissions.

Fuel life cycle assessment (LCA) studies conducted since the 1980s have examined the energy inputs and GHG emissions associated with transportation fuels. They have included only preliminary estimates of the CO_2 release from land use conversion (LUC) associated with biofuel crops. These studies have evolved into several models that address the direct fuel cycle or well-to-wheel (WTW) emissions. Models, such as the **G**reenhouse gas, **R**egulated **E**missions, and **E**nergy use in **T**ransportation model (GREET) from Argonne National Laboratory, or the Joint European Commission's Joint Research Centre/EUCAR/CONCAWE (JEC) analysis for the European Union (EU), provide the basis for assessing well-to-wheel (WTW) emissions from various fuel options.

In addition, several agro-economic modeling systems were adapted to assess the effect of changes in the agricultural system on land use and GHG emissions as a result of biofuel production. Models such as the **F**orest and **A**gricultural **S**ector **O**ptimization **M**odel (FASOM), the **F**ood and **A**gricultural **R**esearch **I**nstitute (FAPRI) model, and **G**lobal **T**rade **A**nalysis **P**roject (GTAP) model are used by regulators to assess the impacts on global agriculture due to biofuel policies.

Objectives

The objective of this study is to provide an assessment of existing life cycle analyses of transportation fuels, including a review of methodologies, analytical tools, and models. This project scope includes identifying gaps in existing methodologies, data tools, and models, and comparing their assumptions and limitations. This study reviews the published studies, which have received the greatest policy attention. The underlying models, documentation, and related papers, and input assumptions are also examined.

Scope

The study first examines various LCA studies and their approach to key aspects of fuel cycle modeling. The WTW results are disaggregated to examine the differences in the model inputs, function, and approach. Then the strengths and weaknesses of various LCA models, including assumptions (realism and documentation), structural approach, transparency and ease of use, and limitations and gaps are examined. Next, the study identifies LCA issues affecting biofuels such as average versus incremental energy carriers, co-product credits, regional specific emission factors, and GHG species that can have a significant impact on the results for fuel LCAs. Finally, the treatment of direct and indirect emissions related to biofuels production is examined.

The study provides recommendations for further life cycle analysis work. This summary reviews the issues, data gaps, and recommendations for fuel LCA models. The overview is grouped by issues that significantly affect WTW models such as GREET and the JEC's transport fuel calculations. Issues affecting land use are summarized next. Data gaps and recommendations for additional research are discussed at the end of this summary.

WTW Models

WTW models estimate fuel cycle GHG emissions based on the energy inputs and losses for fuel production pathways. The models follow the same general calculation technique, but the results for comparable pathways differ significantly. The wide variation in results is due to many factors. Some variation is due to differences in process inputs such as fertilizer application, fuel production yield, and transport distance. However, most of the differences are due to the approach taken by the model or study.

What causes the difference among fuel LCA models?

- Different scenarios (plant technology, time frame, region, transport)
- Assumptions on conversion yields
- Different methods for co-products including oil refinery, animal feed, glycerin, and electric power
- Approach to agricultural N_2O
- Differences in regional resources
- Differences in scope (GHG species counted)
- Errors

One of the most important differences among fuel LCA models (and fuel LCA polices) is the treatment of co-products[1]. The preferred method for the treatment of co-products is to subtract the substitute value of the co-product from the primary fuel product. Allocating energy inputs and emissions based on the mass, energy, or economic value of the co-products allows for a simpler consistently applied calculation. The range of allocation schemes is applied among the various fuel LCA models.

[1] Co-products are produced from the same production facility where fuels are produced. Examples are corn distiller's grains, glycerin, electric power, or fuels such as LPG. One method of determining their substitute value requires a life cycle analysis of the displaced product (i.e., the "substitution" or "displacement" method). Emissions can also be allocated according to energy, mass, or economic value. However, this "allocation" approach is deemed less desirable because it may not reflect the environmental consequences of producing co-products as accurately as the substitution or displacement method.

The JEC, LEM (Life Cycle Emissions Model), GHGenius (Canada version of LEM), GREET, ARB's LCFS, and the EPA's RFS2 (revised Federal Renewable Fuel Standard) use variations of a substitution analysis for most fuel pathways. The allocation method is also used for some GREET and LCFS pathways. The EU Renewable Energy Directive uses an energy allocation approach in order to provide for a simpler calculation method.

For grain ethanol, key differences are due to the treatment of LUC and credits for distiller's grains and solubles (DGS) co-products illustrated in Figure S.1. The difference in co-product credit between the California Air Resources Board (ARB) CA-GREET and the Argonne National Laboratory (ANL) version are due to assumptions about the amount and type of feed displaced by DGS. The model inputs also differ in their approach to regional data for electric power. However, this has a relatively modest impact on the outcome of the analysis.

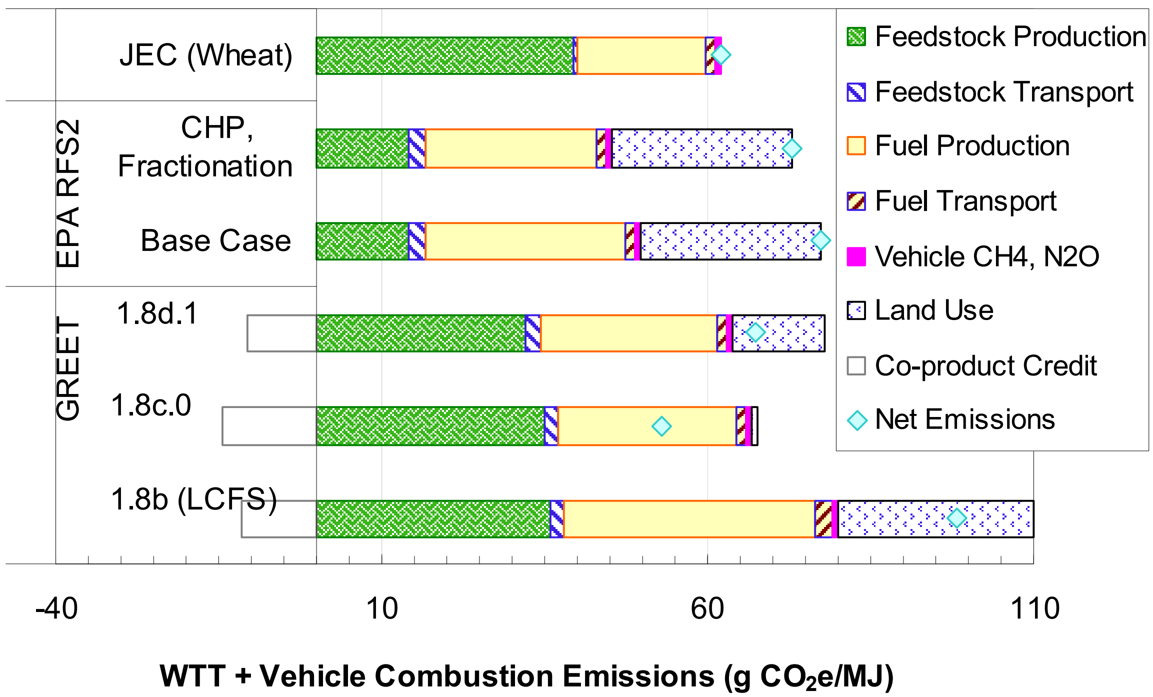

Figure S.1. GHG Emissions from Grain Ethanol (WTW plus LUC results)

Even assessing the GHG emissions outputs among different models is a challenge. Identifying the inputs and disaggregating the results is extremely challenging because the models and studies use different methods of reporting and aggregating inputs and results.

WTW Issues

Table S.1 lists many of the issues with the WTW or attributional life cycle analyses associated with fuels. Spreadsheet WTW models are generally limited by their calculation structure and difficulty in defining inputs. BESS (Biofuel Energy Systems Simulator Model) and JEC studies provide the most transparent inputs, and the JEC database calculation approach allows for more flexible calculations. The life cycle results from JEC used for the EU Directive are provided in the BioGrace (EU Renewable Directive) model, which provides a summary of the life cycle inputs and upstream emission factors.

The structure of fuel LCA models affects their calculation flexibility and usability. GREET, GHGenius, and LEM provide an endogenous spreadsheet calculation of the life cycle inventory of most process fuel inputs such as natural gas, fertilizers, etc. The spreadsheets become complicated with size and the specification of parameters such as regional detail become difficult to implement. BESS and BioGrace are simpler to understand, but their scope is simpler than that of the complete WTW models.

Many issues affect the LCA results for biofuels, petroleum fuels, and inputs to the fuel cycle. Feedstock and fuel input parameters are subject to regional variability and plant-to-plant variability as well as variability in data quality. Key biofuel issues include agricultural practices, soil carbon (emissions and storage), and agricultural methane and N_2O emissions. The treatment of the co-products and emission impacts from indirect activities remain an issue with all fuel pathways.

A key LCA input is the life cycle inventory of inputs such as natural gas, fertilizer, electric power, and co-products. Credits for co-products such as animal feed vary with the allocation systems used as well as the life cycle of these products. Issues of co-product allocation and resource mix are also addressed in the LUC analysis where economic models predict the effect on agricultural systems. These analyses focus primarily on the market effects on agriculture, with only limited assessments of the impacts on natural gas, fertilizer and electric power economics, and production capacity.

Crop cultivation results in significant nitrogen impacts associated with fertilizer and manure use, crop rotation, and residue use. Soil N_2O emissions are one of the most significant GHG contributors and one of the most poorly characterized sources to date. In terrestrial ecosystems, several nitrogen-species, including nitrates and ammonia, are nitrified or denitrified into N_2O, a potent long-lived GHG.

For example, LEM treats nitrogen deposition, leaching, and nitrogen transfer between different ecosystem types and estimates the associated N_2O emission rates for each ecosystem. Data in LEM show that the uptake of N and subsequent conversion to N_2O varies by an order of magnitude depending on whether the ecosystem is nitrogen-limited. The variation in nitrogen behavior and impacts highlights the need for regionally-specific data describing the nitrogen balance in different ecosystems.

GREET calculates N_2O, based on applied nitrogen and nitrogen in the crop residue for the average crop inputs, while JEC uses a nitrogen model to estimate the N_2O emissions from the marginal crop associated with biofuel production.

Table S.1. Issues with Fuel LCA Analysis

Category	Issue/Model Characteristic
Model calculations	• GREET, LEM, and GHGenius spreadsheet models with endogenous life cycle inventory (LCI) of GHG species and criteria pollutants. They are difficult to maintain, error check, and adapt to new pathways. • BioGrace is a spreadsheet model of JEC pathways. Exogenous LCI data. • BESS is a spreadsheet model for corn ethanol with detailed user interface and exogenous LCI data. • Documentation of assumptions is extensive but requires more detail and updates. • Various approaches to WTT recursion and regional detail.
Co-product treatment	• No universal agreement on treatment of co-products in LCA models and EPA, ARB, and JEC analyses • Unintended consequences for co-products such as improved (reduced) LCA score with lower fuel production yield • Uncertain impact of feed products • Potential for double crediting under other programs such as the sale of green power credits • Potential for dissimilar treatment in WTW and LUC models
Alternative fate of feedstocks and co-products	• Uncertain fate of waste materials absent biofuel production. Tallow, used cooking oil, biomass, and landfill gas could become feed stocks for power production or boiler fuel for other processes. • Use of MSW as feedstock affects land fill emissions.
Approach to N_2O	• IPCC (Intergovernmental Panel on Climate Change) method for N_2O based on applied chemical fertilizer (used in GREET) • JEC, FASOM predict N_2O from agricultural models • N_2O from biogenic fertilizers is not counted; however, fate of nitrogen in manure is variable • Difficult to predict field and downstream N_2O emissions from fertilizer
Regional resource mix	• Inconsistent treatment and aggregation of data, especially farm inputs and electricity mix (national, state, county, farm)
Attributional vs. Consequential LCA (CLCA)	• CLCA requires complex suite of models that are difficult to integrate • Marginal vs. average resource mix • Constant food and fiber supply or competition with biofuel feedstocks for food and fiber • Other indirect effects of fuel production including fertilizer, natural gas, and renewable power resource use
Other GHG species	• Radiative forcing of pollutants such as particulates and secondary effects such as ozone are recognized by IPCC as GHG impacts • Regional effect of secondary emissions is variable • Many secondary GHG species depend upon regional criteria pollutant emissions and secondary ozone formation
Life cycle of chemical inputs	• All chemical inputs are not counted in biofuel LCA models. • Fertilizer is assumed to be from natural gas when growth is in production from coal.

Analysis Gaps

Many of the issues with fuel LCA could be addressed with additional research. Some of the gaps are identified in Table S.2. Recommendations to address these gaps are identified in the report. Some of the key areas of research would address the methods for allocating co-products from fuel production.

Another critical area is the development of an analysis of indirect effects of energy carriers and fertilizers that is consistent with the analysis of LUC. Finally, data inputs and consistent methods for analyzing uncertainty should be improved.

LUC Models

Land use change (LUC) is an important element of a biofuel's life cycle impact. It includes the direct emissions associated with land conversion to agricultural fields and indirect emissions associated with economic impacts induced by the land use change. LUC and other indirect effects are treated as economic phenomena. To date, most of the effort has focused on integrated direct and indirect land use conversion (iLUC) as the initial estimates indicate potentially large GHG emissions.

iLUC is predicted by economic models that represent food, fuel, feed, fiber, and livestock markets and their numerous interactions and feedbacks. Results from large-scale economic models, however, depend on a wide range of exogenous variables, such as growth rates, exchange rates, tax policies, and subsidies for dozens of countries. Other indirect effects include the effect of fuel inputs, such as natural gas for fertilizer or electric power, on global energy systems. A final category of indirect effects includes social phenomena attributed to fuel production that are not addressed in modeling efforts.

The analysis of iLUC and other indirect fuel cycle inputs and effects is grouped into a category of consequential LCA (CLCA). The CLCA aims to identify the inputs on the margin of production such as the land required to grow crops that replace any crops used for biofuel production or the fertilizer required to grow new crops. Ideally, CLCA takes into account the global agricultural, food, economic, and energy system. The EPA's RFS2 analysis is identified as a CLCA while WTW models that calculate the direct inputs for fuel production (and their upstream fuel cycle components) are considered attributional LCAs (ALCA). The distinction is not clear as many WTW models use inputs that reflect marginal resources (such as electricity mix). Also, CLCA models do not capture all of the inputs on the margin.

Table S.2. Fuel Life Cycle Model Data Gaps

Data Gap	Recommendation
Agricultural inputs	• Collect National Agricultural Statistics Service (NASS) level data on agricultural inputs globally • Develop estimates of fertilizer trends based on agronomics
Process data	• Collect and validate data from biorefineries and other fuel production facilities • Perform life cycle analysis of fertilizers and chemical inputs and correct errors in the LCA models
Co-products	• Examine the relative value of feed co-products including high protein DGS and other biochemicals • Develop consistent approach for the attribution of co-produced electricity to biofuels and alternative use of waste feedstocks • Develop a consistent methodology for co-product treatment
Nitrogen cycle	• Model nitrogen and carbon cycle including the fate of nitrogen fixation, manure, and other organic materials • Develop regionally specific detail to N_2O emissions to apply to LCA models
Model integration	• Develop fuel LCA models that examine a range of approaches to carbon stocks, N_2O, co-products, other GHG species, and other parameter in order to facilitate harmonization among global fuel LCA policies. • Develop database structure for fuel LCA models to improve transparency, calculation efficiency, and sensitivity analysis.
Other GHG species	• Develop regionally specific data for emission factors that provide the inputs to calculate other GHG species such as PM as well as indirect GHG species such as ozone. • Develop a calculation tool similar to LEM that addresses the time dependence and inventory of GHG species.
Economic indirect effects	• Examine all energy and fertilizer inputs in macro-economic models. • Address capacity expansion for fertilizer, natural gas, and electric power production. • Model marginal resources such as unconventional gas, and resource changes for fossil fuels.
Other indirect effects	• Examine fertilizer depletion, electric power capacity expansion, fossil fuel resource availability, and supply/demand effects.
Uncertainty analysis	• Develop tools for uncertainty analysis including stochastic analysis, analysis of probability inputs, output, and data structures for probability distribution functions. • Employ uncertainty analysis that preserves the asymmetrical nature of many phenomena (don't just apply an average with a bell curve).

Note that many of the data gaps are closely linked to the LUC analysis discussed in the following section.

Predictions of LUC involve the calculations of land cover changes using agro-economic models such as FASOM[2], FAPRI, GTAP, or others. Land cover predictions are combined with estimates of carbon stock changes from existing land to new agricultural practices. Figure S.3 illustrates some of the variability in calculating land conversion for scenarios with corn ethanol. The model results depend on the elasticities that affect the trade between food commodities, approach to trade barriers, and predictions of yield improvement. The combination of these effects results in LUC emissions, which occur over time. These emissions are then amortized over a timeframe.

What are the sources of variability in LUC analysis
🛠 Inconsistency between WTW and CLCA inputs (e.g., co-product credit vs. market effect, average vs. marginal fertilizer and electricity inputs). 🛠 Bundled results embed many model assumptions, which are difficult to understand. 🛠 Different approaches to yield projections. 🛠 Uncertainty in induced yield improvements due to fuel policy/crop expansion/price. 🛠 Regional variation in carbon stocks. 🛠 Challenge in defining land classes. Extremely difficult to match Winrock (2009) analysis and satellite data with GTAP agro-economic zones. 🛠 Approach in treatment of marginal land and pasture. 🛠 Treatment of time is user assumption with proportional effects on LUC outcome. 🛠 Impact of burning, harvested wood products, rotting, and methane. 🛠 Treatment of agricultural trade between countries.

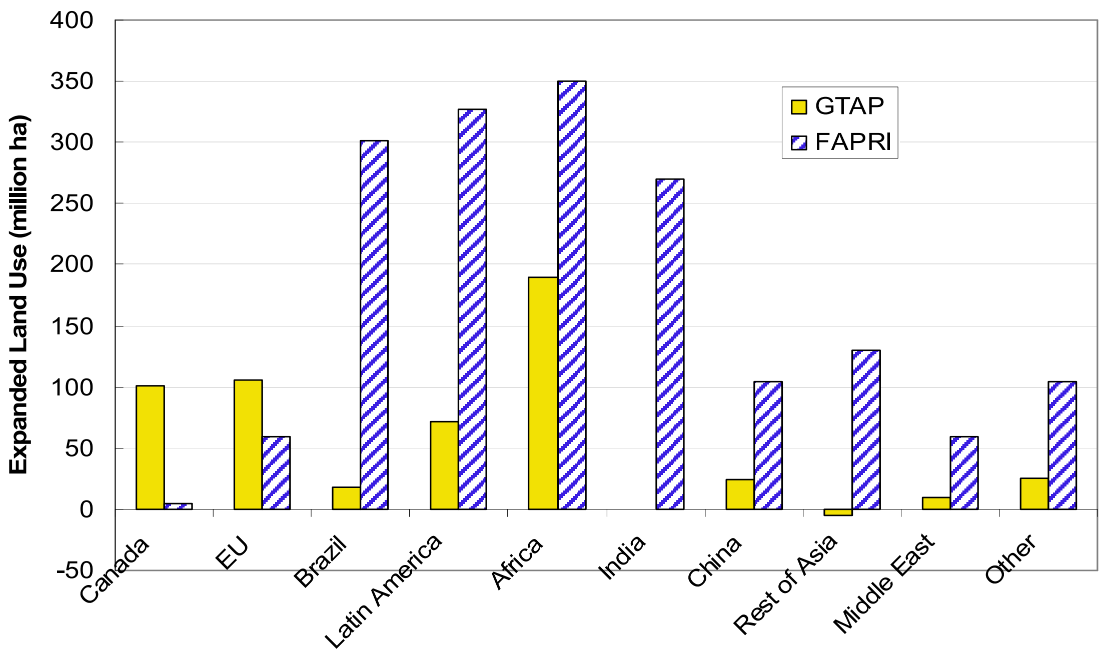

Figure S.3. Land Conversion Predictions due to Corn Ethanol Production Changes from GTAP and FAPRI (Source: Babcock 2009)

EPA's modeling of biogenic greenhouse gas (GHG) fluxes associated with agriculture include the storage of atmospheric carbon in plant biomass due to photosynthesis, respiration,

[2] FASOM performs these calculations internally plus takes into account agricultural inputs.

decomposition, and the uptake or release of carbon into roots, soil, and/or back to the atmosphere. Non-CO_2 GHG emissions (CH_4, N_2O) from agricultural practices vary depending on the management practice employed. The uptake of atmospheric CO_2 into plant material is considered a credit against the biogenic carbon in the fuel. However, the biogenic components of feedstock production and land use are important elements of a biofuel's life cycle impact. While the phenomenon of LUC is widely examined, many issues surround the models and calculations as summarized in Table S.3. Estimates of LUC include widely different estimates of yield response to increased agricultural activity, regions where LUC occurs, and emissions associated with land conversion.

Table S.3. Issues with iLUC Estimates

Category	Issue
Carbon stocks data	• Inconsistent results and emission factors for Winrock (2009) and Woods Hole (2000) data used by EPA and ARB. • Winrock (2009) analysis uses more detailed regionally specific predictions of land cover type and carbon release; although many data categories are broad simplifications. Newer soil data are available. • ARB uses less detailed data from Woods Hole that is matched to GTAP regions. Omits CH_4 and N_2O impact of burning to clear land. • FASOM model calculates land conversion emissions internally. • No clear approach for attribution to harvested wood products.
Succession of land to agriculture	• Difficulty in modeling conversion of marginal land. • Intensification of cattle on pasture land is difficult to model.
Yield Improvement	• GTAP uses macro economic projections of yield to price and yield to area expansion plus additional factors for technology-based yield improvements. • FASOM estimates yield for each region in the U.S. while FAPRI yield changes are much smaller than those used for GTAP.
Identification of converted land	• GTAP predicts land cover type based on economic prediction. • EPA combines regional land prediction with land cover types based on satellite data. • Attribution of deforestation to agriculture.
Allocation of time variant emissions	• GHG reductions from biofuels may occur over many decades but short term carbon release from iLUC can be significant. • Reversion of crop land to natural land is not symmetrical with conversion of natural land to crops.
Food effects	• Principal economic model results do not hold food production constant, thus providing a GHG benefit for producing less food.

LUC Analysis Gaps

The largest uncertainties in fuel LCA are associated with the calculations of land use emissions. Table S.4 below summarizes the main data gaps and areas for improvement of the LUC analysis models.

The assessment of carbon stocks can be improved as more regionally specific data become available. Data that approach the IPCC (Intergovernmental Panel on Climate Change) Tier 2 level of detail should be used to update carbon stock databases such as the Winrock (Winrock International 2009) analysis. The LUC models such as GTAP should allow for the flexible use of different LUC approaches including the Winrock analysis, although the mapping of regionally specific data to GTAP regions is challenging. Models should also be developed to accommodate other methods of estimating carbon stock changes such as national primary productivity (NPP) based models including CENTURY (Soil Organic Model) and DAYCENT (daily version of CENTURY Model). The representation of process data and economic inputs to agro-economic models and their outputs should be treated in an integrated model. Finally, the factors that determine price-induced yield should be based on economic observations and validated.

Efforts to better understand carbon stocks and related GHG emissions will improve over time. Many of these improvements will occur with research not related to fuel LCA. The challenge will be to incorporate more detailed and complex representations into fuel LCA models.

Table S.4. Key Data Gaps in LUC Modeling

Data Gap	Recommendation
Carbon stock and agricultural effects	• Develop regionally detailed analysis for GTAP regions and agro-economic zones (AEZs). • Examine different carbon stock and emission release approaches. • Review carbon stock data to examine differences in models, uncertainties, and factors such as harvested wood and CH_4 impacts. • Apply Winrock (2009) carbon stock factors and calculations to GTAP regions. • Develop tools to examine different carbon stock datasets and predictive models with spatial LUC models. • Adapt evolving regional Tier 3 analysis to regionally-specific carbon stock models. • Develop a model that facilitates better spatial analysis of carbon stock changes, fertilizer application, and N_2O formation.
Methanogenic activity	• Determine effect of land cover change on methanogenic sources such as anaerobic decay and termites.
Macroeconomic model inputs	• Develop methods to relate econometric data to process data for existing and new biorefinery and fuel production technologies. • Develop simple (reduced form) LUC/ILUC calculation tool that enables transparent representation of carbon stock and land conversion factors. • Develop econometric model of energy inputs to conventional and biofuels including natural gas, petroleum, coal electric power, and fertilizer sectors including constraints on resources and production capacity. • Develop a reference case for LUC modeling comparison. • Develop approaches to validate inputs and intermediate projections such as yield improvement.
Standardized framework	• Provide a consistent basis for reporting inputs, outputs, elasticities, and predicted factors such as yield among LUC models.
Sustainability	• Identify the relationships between deforestation, agriculture, and the succession of land. • Examine LUC effects with constant global food supply. • Develop a method for categorizing social indirect effects such as road construction, environmental degradation, food, and fuel price effects[1].
Price induced yield	• Develop data to support elasticity factors to model price-induced yield. • Relate econometric data to physical data.
Time horizon	• Determine a standardized and consistent time horizon and discount rate for comparing fuel pathways. • Address dissimilarity between GWPs for GHG species, time horizon for biofuel projects, and targets for GHG reductions. • Develop dynamic (temporally variable) LCI data and use time-dependent LCA inputs to determine CI scores for any time horizon.

[1] Broader categories of effects are often introduced in the context of GHG emissions and alternative fuels. Most fuel LCA models do not address these effects and their inclusion in a GHG rating is considered a matter of policy by regulators.

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1. Introduction

Interest in the greenhouse gas emissions from transportation fuels is increasing with concerns over global warming, resource scarcity, and government policies that support low carbon intensity (CI) fuels. CI is defined as the life cycle greenhouse gas (GHG) emissions of a fuel pathway starting with feedstock production all the way through to the use of a finished fuel in a vehicle. CI has units of mass of carbon dioxide equivalent life cycle emissions (g CO_2e) per unit of finished fuel energy in a vehicle fuel tank (Mega Joule (MJ) finished fuel), or g CO_2e/MJ[3]. Understanding and comparing GHG emissions from different fuel options requires a life cycle or well-to-wheels (source to wheels) analysis, including all steps from feedstock production to vehicle end use as illustrated in Figure 1.1 for petroleum fuels. This analysis covers the energy and emissions generated during the steps required to deliver finished transportation fuels, produced from a variety of feedstock sources, to the vehicle and includes the subsequent combustion of the fuel in the vehicle. It also covers the combined model approach of including land use change (LUC) effects in full fuel cycle analyses[4].

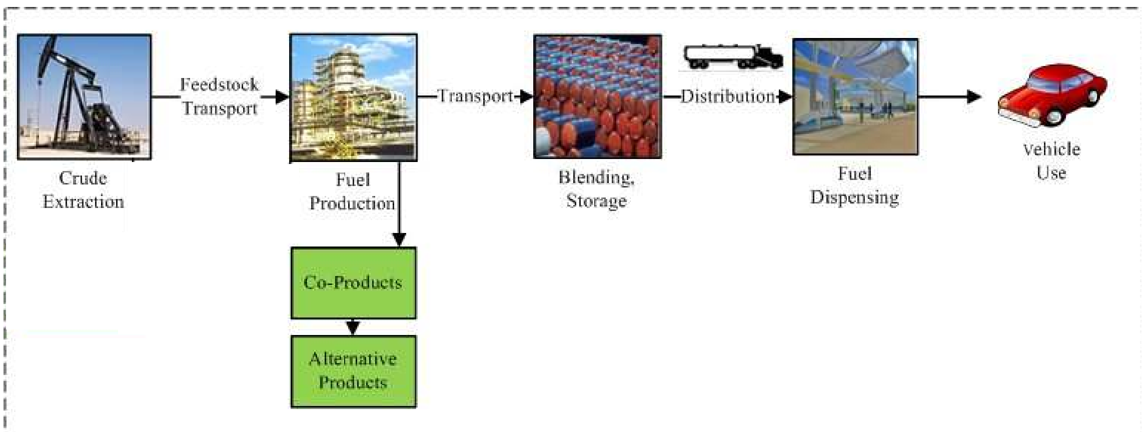


Figure 1.1. Steps in Well-to-Wheel Emissions Analysis.

1.1. Background

WTW emissions include those associated with the production and end use of a fuel. A fuel cycle analysis typically includes impacts related to the production of feedstocks, feedstock transport, fuel production (e.g., refining for petroleum fuels), fuel transportation and distribution (T&D), and vehicle fuel consumption. The carbon intensity of a transportation fuel depends on the energy inputs to the fuel production system as well as feedstock inputs (e.g., agricultural inputs

[3] The term WTW generally refers to vehicle emissions represented in g/mi, which takes into account vehicle energy consumption as well as vehicle CH_4 and N_2O emissions. The GWP for these components are 25 and 298 respectively. The CI is expressed in g CO_2e/MJ and also includes vehicle CH_4 and N_2O emissions. CI values can be adjusted for vehicle fuel efficiency for example with hydrogen or electric powered vehicles.

[4] LUC takes into account the conversion of new land to produce biofuels or the indirect conversion of land (iLUC) to provide crops that are displaced by biofuel production. iLUC satisfies the demand for the crop diverted to biofuel production on existing cropland.

for biofuels), treatment of co-products, location-specific parameters (e.g., electricity grid), and fuel blending processes. The impact of building fuel production facilities, and vehicle production and recycling, are generally excluded from fuel life cycle analyses (LCA), or are considered separately.

Examining upstream fuel cycle emissions (those associated with all processes up to and including fuel production) for alternative fuels is particularly important for biofuels because significant energy inputs and emissions are usually involved in the production of biomass feedstocks and biofuel production processes. Downstream of fuel production, the carbon released during biofuel combustion is comprised of that which was removed from the atmosphere during biomass feedstock growth. Thus, this carbon is not considered to contribute to global warming. However, increased biofuel production may induce changes in the release of soil carbon, in addition to indirect effects of the fuel production cycle elsewhere.

1.2. Life Cycle Analysis of Fuels

Fuel LCA models that analyze a range of alternative fuels have evolved as interest in comparing the life cycle GHG emissions of different fuel options developed. These WTW models allow for a consistent application of assumptions for all of the feedstocks in the fuel chain within each model. Fuel LCA models evolved over the years to support a general understanding of transportation issues, developments in new vehicle and fuel technologies, and government transportation fuel policies. The evolution of fuel LCA modeling work over the past two decades is illustrated in Figure 1.2. WTW and fuel LCA studies have been used to compare the impact of alternative fuels. Many studies in the 1990s focused on the criteria pollutant emissions impacts of electric transportation, followed by examinations of other alternative fuels, including methanol, ethanol, biodiesel, and hydrogen.

Most of the life cycle analysis models are spreadsheet-based. The GREET model was developed at Argonne National Laboratory (ANL) by Michael Wang and his team and first released in 1996 (Wang 1996). LEM was developed by Dr. Mark Delucchi at the University of California, Davis (Delucchi 2003). The GHGenius model, developed by Delucchi for Natural Resources Canada (Delucchi 1998) is based on an early version of LEM, though it has been updated, most recently in 2010 ($(S\&T)^2$ 2010). These three models share many primary data sources and are the main spreadsheet-based models used in WTW analyses.

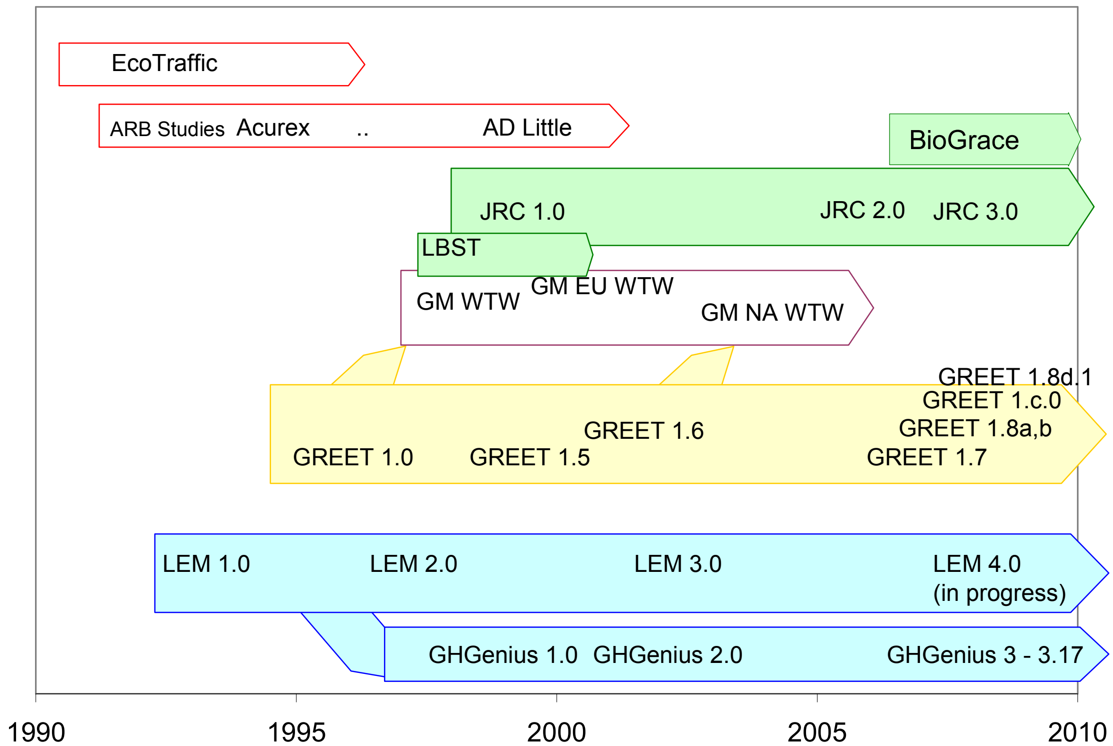


Figure 1.2. History of Fuel Life Cycle Models

Other approaches to LCA involve using a database of life cycle inventory (LCI) information to determine the parameter values to employ in estimating energy use and emissions associated with inputs to a fuel chain. The European General Motors (GM) WTW study adopted the database approach, combining life cycle emission factors with alternative fuel process parameters (LBST 2002). The LCI data were based on the E3[5] European database from Ludwig Bölkow Systemtechnik (LBST). This approach evolved into the study by the Joint Research Centre (JRC), the European Council for Automotive Research and Development (EUCAR), and CONservation of Clean Air and Water in Europe (CONCAWE) for JRC in Europe (JEC). These and other studies are listed in Table 1.1.

[5] Germany, United Kingdom, and France, the three European countries with the largest populations and economies

Table 1.1. Life Cycle Studies and Models

Study	Model/Database
JRC/EUCAR/CONCAWE (JEC 2008b)	JRC/LBST database
GM/ANL 2001 (Wallace, et al. 2001)	GREET
GM/LBST 2002 (LBST 2002)	LBST database
GM 2005 (Brinkman, et al., 2005)	GREET
UCD/LEM (Delucchi 1997-2006)	LEM
CEC/TIAX (TIAX 2007)	GREET
ARB LCFS (ARB 2009a)	GREET
EPA RFS2 (EPA 2010a)	GREET
GHGenius ((S&T)^2 2006)	GHGenius
BESS (Cassman 2008)	BESS

Other fuel LCA studies and models have been conducted over the years in considerable detail, including efforts by Ecotraffic (2001), Acurex (Unnasch, et al. 1996), Price Waterhouse & Coopers (2003), and Arthur D. Little (ADL) (Unnasch, et al. 2001). Many have fallen into disuse or are not available.

Several WTW studies have examined the impacts of alternative fuel options, including a collaborative effort between GM and ANL, as well as a recent study by the University of California, Davis (UCD). The studies, also listed in Table 1.1, vary with regard to inputs, vehicle technology, and well-to-tank (WTT) calculations. These studies examined a variety of fuel options for different vehicle production scenarios. The GM/ANL and California Energy Commission (CEC) studies performed by TIAX used GREET. So did the work performed by the California Air Resources Board (ARB) to implement California's low carbon fuel standard (LCFS), and by the U.S. Environmental Protection Agency (EPA) to establish the revised Renewable Fuel Standard (RFS2). Similar to other models referenced in Table 1.1, such as the Biofuel Energy Systems Simulator (BESS) model developed by researchers at the University of Nebraska, Lincoln (UNL), GREET is a spreadsheet-based (Microsoft Excel ™) model that calculates the LCI data internally for use in life cycle analyses, rather than referencing a database. The European GM/LBST and JRC, EUCAR, and CONCAWE (JEC) studies rely on the LBST life cycle database to generate fuel cycle results. The LBST data reflect European input assumptions and the details of the modeling approach differ from GREET.

GHGenius, originally developed by Delucchi, has been maintained and updated by (S&T)^2 under contract to Natural Resources Canada since 1998, and used to model fuel cycle emissions of Canadian fuels. Delucchi continued to build the LEM from the early version embodied in original GHGenius. In 2001, Levelton worked with Delucchi to expand GHGenius to be capable of projections to the year 2050, added Mexico to the model, and added the capability of regional analysis for Canada and the United States. Since 2004 GHGenius has been continually updated by (S&T)^2. LEM and GHGenius are much more complex than other LCA models and offer greater functionality. This includes representation of over 20 different geographic regions and soil types, nitrogen and sulfur tracking through biosystems after atmospheric deposition, indirect greenhouse gas impact calculations, and dynamic representation of the atmosphere and its major constituents over time. The climate impact of greenhouse gas emissions varies over time in LEM, which yields life cycle emission results that are much more difficult to assess than the simple analyses based on the Intergovernmental Panel on Climate Change (IPCC) global warming potentials (GWPs).

LCA models calculate a range of environmental flows, including energy inputs, GHG emissions, criteria pollutants and air toxics emissions, water use, land use, and others. This report compares and contrasts these modeling efforts for LCA analyses of transportation fuels.

1.3. Metrics for Carbon Intensity

Interest in fuel LCA models has grown with initiatives to control GHG emissions in general, as well as to specifically address the GHG emissions from the transportation sector. Life cycle emissions over the fuel cycle are the metric of choice when addressing transportation GHG emissions because both the direct vehicle emissions and the upstream fuel cycle emissions vary considerably among different alternative fuel options. As noted above, fuel cycle greenhouse gas emissions are presented in mass of carbon dioxide equivalents (g CO_2e) per unit of fuel energy produced, (MJ), or g CO_2e/MJ[6].

Table 1.2 lists most of the regulatory policy initiatives aimed at reducing the carbon intensity of fuels. These include the RFS2 regulations being established by the EPA as mandated by the Energy Independence and Security Act (EISA) of 2007; the regulations being established by ARB to implement California's LCFS; the LCFS regulations being considered or established by the Northeast (NE) States, Oregon, Washington, and others; the European Union (EU) Renewable Energy Directive (RED); the United Kingdom (UK) Renewable Transport Fuel Obligation (RTFO); and the Roundtable on Sustainable Biofuels (RSB) certification process. The requirements for GHG reductions are all in terms of life cycle emissions. The results from fuel LCA models are particularly interesting because they are used to determine whether a particular fuel pathway meets carbon intensity (CI) threshold levels.

Table 1.2. Policy Initiatives Involving Life Cycle GHG Emissions from Fuels

Initiative	Requirement
U.S. EISA, RFS2	-36 billion gal of renewable fuel by 2022. -20%, 50% and 60% GHG reduction categories
California LCFS	Reduction in CI of transportation fuels by 10% by 2020
NE States, OR, WA, Other LCFS	Likely comparable to CA
EU Renewable Energy Directive (RED)	10% use of renewable fuels with CI requirements
UK RTFO	10% use of renewable fuels will target for 35% reduction in GHG emissions
Roundtable on Sustainable Biofuels (RSB)	Develops method for counting fuel CI
Sustainable Aviation Fuel Users Group (SAFUG)	Support development of sustainable aviation fuels with carbon neutral life cycle

Other measures aimed at reducing GHG emissions' total emission levels, rather than addressing the emission intensity, are generally not based on life cycle emissions but rather direct mass emissions. Regional and national initiatives include the Kyoto protocol, California AB 32, EU carbon cap, and others.

[6] Some confusion exists over the definition of WTW, WTT, and CI discussed Section 2.1. The WTW and CI values both represent the GHG intensity of the vehicle fuel combination.

Understanding the emission constraints, and harmonizing the approaches among GHG initiatives, is important for several reasons. First, GHG emission factors for GHG inventory programs should be the same as those for fuel LCA because both efforts aim to calculate total GHG emissions. Emissions inventories from power generation, land conversion, and other industrial sectors are also used as inputs for fuel LCA studies. The IPCC GHG accounting methods used for GHG accounting are generally applicable to fuel cycle emissions and specifically applied for LUC carbon stock changes (Section 5). Secondly, the interplay between emission caps and limits with non-transportation initiatives, in principal, affects the assumptions for fuel LCA inputs. For example, the marginal power generation inputs for the California LCFS. The scenarios for consequential LCA discussed in Section 5 also need to be reconciled with emission cap requirements.

Different metrics, emission factors, and carbon accounting methods present challenges in evaluating emissions reductions via different approaches. Some inconsistencies are unavoidable. However, the public should expect that the methodologies used to develop life cycle GHG emissions should be developed and presented in a consistent manner.

1.4. Study Objective

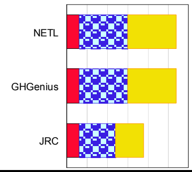
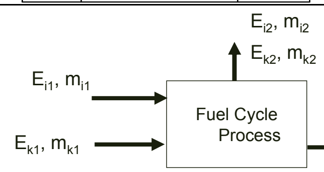
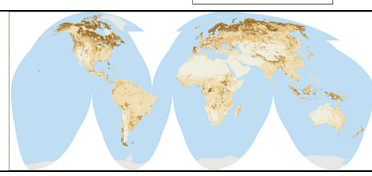
The objective of this study is to provide a broad review of the methods, analytical tools, and models used in transportation fuel life cycle analysis with a particular focus on biofuels. The latest results from the available models are presented, interpreted, and discussed. This study identifies gaps and provides recommendations for improvements in methods, data, analysis tools, and models.

1.5. Report Organization

Table 1.3 summarizes the topic and focus of each of the following sections. The report reviews various approaches to fuel pathway LCA by first examining the direct emissions results from elements in the pathway.

These results are presented in detail as disaggregated WTT plus fuel carbon emissions in Section 2. These provide a clearer view of the differences in various WTW model approaches and their corresponding fuel pathway results. Key parameters affecting each fuel pathway are briefly discussed and significant data gaps are identified for each fuel pathway. Section 3 examines the features and usability of WTW models as well as the merits and issues associated with each approach. Issues affecting the model assumptions and calculations are described in more detail in Section 4. Section 5 describes the issues surrounding land use impacts and their associated GHG emissions. Section 6 provides recommendations for research to improve fuel LCA models as well as suggestions for structural improvements in the models.

Table 1.3. Summary of the Discussion Included in the Following Report Sections

Section	Topic		Focus
2	Fuel Life Cycle Studies		Disaggregate results from LCA studies. Identify difference in key inputs.
3	Model Attributes	Model / Documentation / Rating LEM / -No final report, only 2003 report and 2006 draft report / Results BESS / -Downloadable model with embedded calculations /	Rate usability. Compare calculation structure and outputs.
4	Fuel LCA Issues		Review input data. Review model methods, including co-products, N_2O from fertilizer, vehicle efficiency, GWP, etc.
5	Land Use Change		Review LUC models. Compare land conversion, carbon stock, and LUC calculations.
6	Recommendations	• Document • Review • Calculate	Summarize recommendations and identify actionable research to advance biofuel LCA.

2. Fuel Life Cycle Analysis Studies

The purpose of this section is to identify how various LCA studies approach the key aspects of fuel cycle modeling. This review includes the studies and models listed in Table 2.1 plus the BESS model. The studies listed in the table consider many feedstock/fuel combinations and reflect essentially two models and one database. The CA-GREET model is the standard GREET model modified for use in California, and GHGenius is a modified (and expanded) version of the original LEM parameterized for Canadian fuels. As noted in Section 1, the JEC study is based on the LBST database.

Table 2.1. Comparison of Fuel Life Cycle Analysis Studies – Multi Fuel

Study	Latest Version	Authors/ Organization	Geographical Scope
GREET/EPA RFS2	GREET1.8c.0 (2009)	M. Wang, ANL	U.S. focus
GREET	GREET1.8d.1 (2010)	M. Wang, ANL	U.S. focus
CA-GREET	CA-GREET1.7 (2007)	CEC, TAIX	U.S. with CA focus
	CA-GREET1.8b (2009)	ARB, CEC, Life Cycle Associates	
JEC	2008, v3.0	R. Edwards/JRC, CONCAWE	International with E.U. focus
LEM	2006 report 2003 report	M. Delucchi/ UC Davis	International with country specific
GHGenius	2010, v3.17	D. O'Connor/(S&T)[2]	International with Canada focus
Australia Dept. of Energy	2001, GREET	T. Beer, T. Grant, et al.	Australia

Websites
http://www.transportation.anl.gov/modeling_simulation/GREET/
http://www.arb.ca.gov/fuels/lcfs/lcfs.htm
http://www.energy.ca.gov/ab1007/documents/index.html
http://ies.jrc.ec.europa.eu/WTW.html
http://pubs.its.ucdavis.edu/publication_detail.php?id=273
http://www.escholarship.org/uc/item/9vr8s1bb
http://www.ghgenius.ca/

Table 2.2 summarizes the life cycle studies conducted for a single fuel. Included in the table are studies for the Alberta Energy Research Institute (AERI), the National Energy Technology (NETL) of the U.S. Department of Energy (DOE), the U.S. Department of Agriculture (USDA), the National Renewable Energy Laboratory (NREL), the Institut für Energie- und Umweltforschung (IFEU) Heidelberg, and studies using the EDIP97 (Environmental Design of Industrial Products) LCA model, DAYCENT (a daily version of the CENTURY model), and an LCA model employed by PricewaterhouseCoopers. The petroleum studies considered incorporate many detailed engineering parameters, such as the oil-steam ratio and petroleum API gravity, which are typically excluded from conventional life cycle models (GREET, LEM, and GHGenius).

Table 2.2. Comparison of Fuel Life Cycle Analysis Studies – Single Fuel

Study Group	Model	Pathway	Author
UNL	BESS	Corn ethanol	A. Liska, K. Cassman, (2008)
Jacobs Engineering, AERI	GREET/ Various	Petroleum	W. Keesom, S. Unnasch, J.Moretta (2009)
TIAX MathPro, AERI	GREET/ MathPro	Petroleum	J Rosenfeld, J Pont, K Law, D Hirshfeld, J. Kolb (2009)
NETL		Petroleum	K. Gerdes, T. Skone (2009)
Life Cycle Associates	GREET	Palm oil biodiesel	S. Unnasch, B. Riffel, R. Wieselberg, S. Sanchez (2010)
Schmidt	EDIP97	Rapeseed oil and palm oil	Schmidt (2010)
NREL, DOE, USDA	Various	Soy oil biodiesel	J. Sheehan, V. Camobreco, J. Duffield, M. Graboski, H. Shapouri (1998)
Alberta Energy Futures Project	Hybrid model	Oil sands	J. Bergerson, D. Keith (2006)
Michigan State University	DAYCENT (for soil N_2O emissions)	Corn stover and corn ethanol	S. Kim, B. Dale, R. Jenkins (2009)
NETL, Energy and Environmental Solutions	Various	Coal-derived Fischer-Tropsch (FT) fuels	J. Marano, J. Ciferno (2001)
NREL	Various	Ethanol	K. Kadam (2005)
Shell	PWC	Natural gas FT diesel	PricewaterhouseCoopers (PWC) (2003)
IFEU		Rapeseed oil and palm oil	S. Gärtner, H. Helms, G. Reinhardt, N.Rettenmaier (2006)
ANL	GREET	Soybean oil biodiesel renewable diesel cellulosic ethanol various hydrogen sugarcane ethanol landfill gas oil sands fuels petroleum fuels	M. Wang, C. Bloyd, V. Putsche, H. Huo, N. Wu, et cetera, various publications.

Numerous other studies focus on an individual fuel compared with baseline petroleum. Various models are used in the life cycle calculations. These studies are primarily of interest because they provide additional data and analysis on specific fuel pathways. For example, the BESS model calculates only corn ethanol pathways, but considers a wide range of agricultural scenarios and ethanol plant configurations.

2.1. Overview of Fuel Life Cycle Analysis Studies

This study examines the following LCA models:

- GREET
- CA-GREET
- JEC/BioGrace
- BESS
- LEM
- GHGenius

The versions of these models that are reviewed in this report are given in Table 2.3. In most cases, these are the most recent versions of the models.

Table 2.3. Versions of LCA Models Reviewed

Model	Date
GREET 1.8d.1	Sep-10
GREET 1.8c.0	Mar-09
CA-GREET 1.8b	Feb-09
JEC v3.0	Oct-08
BioGrace v 3 public	2010
BESS 2008.3.1	Mar-08
GHGenius 3.15	May-09
LEM	May-06
Regulatory Study	
ARB LCFS Pathway Documents	2009
EPA RFS2 Final Regulatory Impact Analysis	Mar-10

In addition, a review of the Global Trade Analysis Project (GTAP) model is included in this analysis (see also Section 5). GTAP is a global trade model with a database containing international bilateral trade information for over 40 countries and 50 economic sectors. GTAP is not an LCA model, but it is used especially to determine the impacts of biofuel production on a global economic scale. This makes it possible to assess the direct and indirect impacts of biofuels on the world economy.

Fuel cycle, or WTW, emissions include upstream emissions (WTT) and vehicle operation emissions (tank-to-wheels - TTW). Since vehicle efficiency and use is included in WTW calculations, results can be reported on a per-distance traveled basis, e.g., g CO_2e/km. Table 2.4 shows WTW emissions for fossil fuel, biogas, fuel cell, hydrogen, and electric vehicles. The WTW results in the table incorporate differences in fuel efficiency for different power train options. Emissions results from CA-GREET and GHGenius are generally in close agreement.

However, the JEC emissions results are lower for most fuel options due to the generally higher vehicle fuel economy for European cars compared to U.S. vehicles.

Table 2.4. WTW GHG Emissions from Life Cycle Analysis Studies (g CO_2e/km)

Fuel (Feedstock)	GREET 1.8c.0	JEC	LEM	GHGenius
Gasoline (petroleum)	303	196	289	324
Diesel (petroleum) DI ICEV	263	164	HD Only	270
CNG (NG)	237	149	NA	257
Ethanol (corn) (E100)	203	NA	283	186
Ethanol (wheat) (E100)	NA	115	NA	NA
Ethanol (sugarcane) (E100)	88	25	NA	NA
Ethanol (farmed trees) (E100)	9 (-41)[a]	50	NA	NA
Biodiesel (soy) (B100)	228	NA	HD Only	131
Biodiesel (rapeseed) (B100)	NA	84	NA	NA
Synthetic diesel from natural gas	276	179	NA	279
H_2, compressed, ICEV	289	189	435	389
Electric vehicle	132	NA	378	128
H_2, compressed, FCV	233	98	209	196
Gasoline, HEV	206	140	NF	226

DI ICEV = Direct injection internal combustion engine vehicle. CNG = Compressed natural gas; H_2 =Hydrogen from natural gas steam reformer, NG = Natural Gas; E100 = 100% ethanol; B100 = 100% biodiesel; FCV = Fuel cell vehicle; HEV = Hybrid electric vehicle; NA=Not assessed in the LCA model or not found in the available documentation. Results are for first set of results found in each study. These do not always represent comparable feedstock resources or technology assumptions.
[a]Result in parenthesis includes -112,500 g CO_2e/dry ton wood credit for tree farming assumed in GREET

Many policies aimed at transportation fuels focus on the carbon intensity (g CO_2e/MJ, see Section 1) rather than a per mile emission rate, making the WTW emissions presented in g/mi not particularly useful[7]. Full fuel cycle emissions per MJ of fuel produced are shown in Figure 2.1, including the WTT emissions plus vehicle emissions of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). The ARB uses this metric, considered the CI, to evaluate fuels under the LCFS. The representation in Figure 2.1 does not incorporate differences in vehicle fuel economy, thereby showing differences due to fuel production and processing. The fossil fuel-based results are relatively consistent among models with about 75% of the fuel cycle consisting of carbon in the fuel for petroleum-based gasoline and diesel. Therefore even the small variations in both the natural gas and diesel results represent a relatively large fraction of the WTT emissions.

Emissions from biofuel pathways are completely inconsistent among the models. The addition of land use change emissions complicates the comparisons further. The reasons for these differences are discussed in detail later in the report.

[7] California's AB 1493 regulates passenger car GHG emissions on a per mile basis with an adjustment for alternative fuel life cycle GHG emissions.

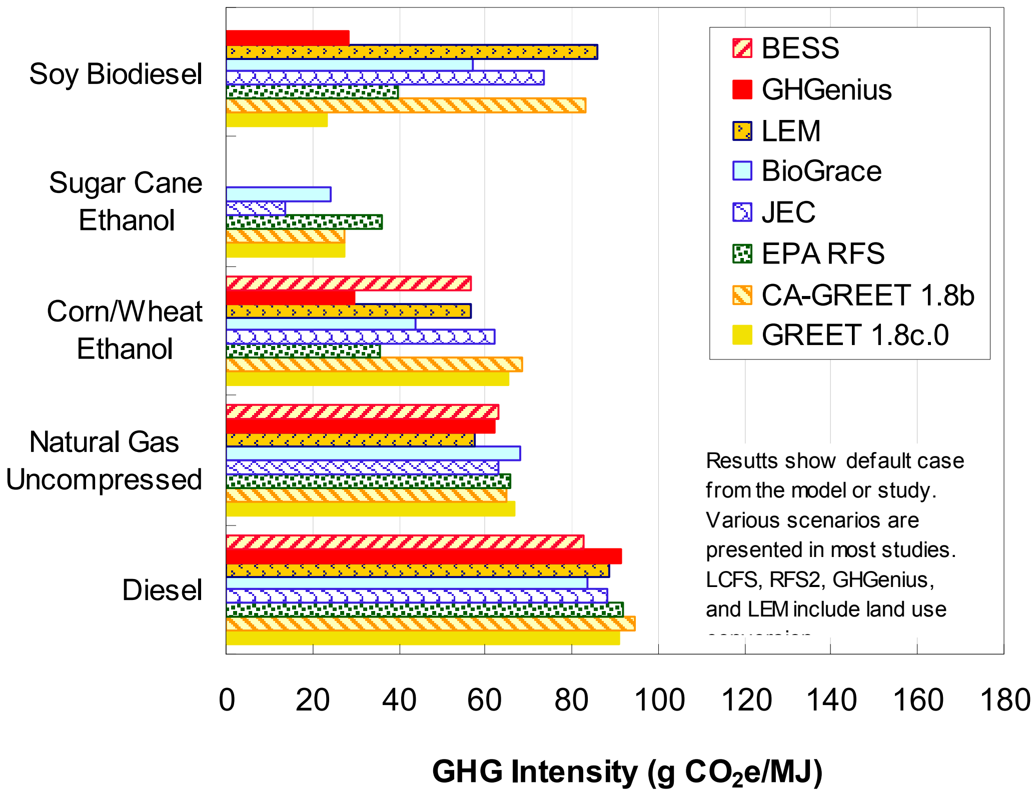


Figure 2.1. WTW GHG Emissions (g CO_2e/MJ) for Fossil Fuels and Biofuels.

To compare fuels used in different vehicle technologies, including gasoline and diesel drop-in fuels, energy economy ratios (EER) are used to adjust the CI based on the ratio of the vehicle energy use of the baseline gasoline or diesel vehicle to that of an alternative fueled vehicle (vehicles with EER values greater than one are more energy efficient than the baseline vehicles).

Briefly, the major differences in model results among the biofuels are due to:

- Inclusion of LUC and method
- Co-product allocation methods for animal feed, electric power, and glycerin
- Biorefinery process energy inputs including process efficiency
- N_2O emissions from chemical and organic fertilizer application and nitrogen fixation
- Feedstock conversion to biofuel yields

Differences in the range of 0.5 to 2 g CO_2e/MJ are also due to:

- Transport logistics
- Vehicle CH_4 and N_2O emissions
- Fuel properties[8]

[8] Minor differences and errors in fuel properties are apparent in fuel LCA models. The most significant variability is in the carbon content of coal used for power production. The data and unit conversions warrant better documentation.

2.2. Fuel Life Cycle Analysis Calculations

Fuel cycle analysis begins with a unit of fuel produced, moving upstream to the fuel production processes, feedstock transport, and feedstock recovery or production steps. The steps in the pathway require process energy inputs and include losses at each step in the pathway as a result of process inefficiencies. Losses in either feedstock or fuel affect the overall production efficiency. Figure 2.2 shows the total (direct and upstream) process energy and the energy contained in an example of biofuel produced. The figure indicates flow (energy, mass, emissions) and the width of the arrows indicates the relative magnitude of the flow; the figure illustrates the feedstock energy required to generate one unit (e.g., MJ) of fuel and the energy requirement for each pathway step. Each step in a fuel pathway is composed of smaller unit processes, such as oil extraction and oil transesterification in a biodiesel plant.

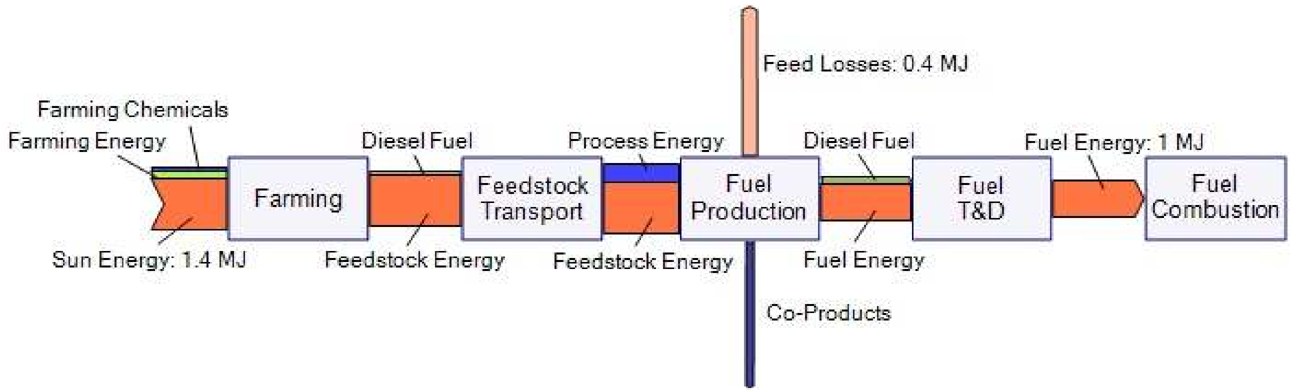


Figure 2.2. Fuel LCA Calculations Track Process Inputs Throughout the Fuel Chain

Figure 2.3 illustrates the fundamentals of an individual unit process in an overall alternative fuel production process. Energy and mass flow into the unit process and exit the process in one to several product streams. Emissions result from process fuel use and feedstock losses; these are represented by emission factors in the life cycle analysis, which indicate the mass emissions (g) per unit of fuel consumed (MJ). The fuel cycle analysis includes all the upstream fuel cycle inputs to produce the fuel. For example, the upstream burden for methanol production (required in the transesterification process) is included in the calculations for biodiesel fuel. The life cycle models considered perform similar calculations to account for direct and upstream emissions. The calculation differences are discussed in Section 3. The following discussion compares the model results for biofuels as well as the fossil fuel inputs for fuel production.

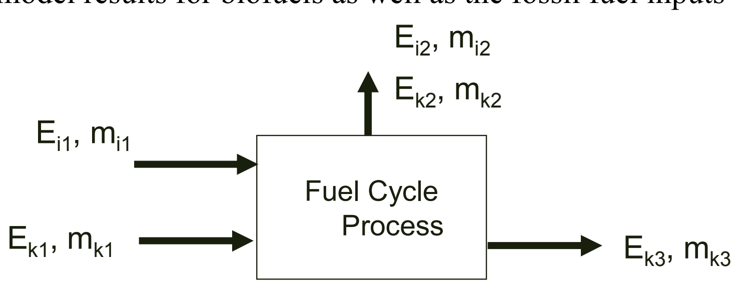


Figure 2.3. Illustrative Energy and Mass Unit Process Flow Diagram in a Fuel Production Conversion Step (Source: Life Cycle Associates, consistent with Wang 2005, Unnasch 1996).

2.3. Results and Key Inputs

Selected fuel pathway WTT and TTW emission results are presented in Table 2.5. These values are depicted in fuel cycle charts by fuel type throughout the next several subsections. For fossil fuels, fuel carbon in the fuel is responsible for the majority of fuel cycle emissions. The CI values for biofuels, in contrast, are nearly entirely due to WTT emissions because the fuel carbon is biogenic.

Different versions of the GREET model are used in the analyses for the California LCFS and the EPA's RFS2 analysis. The EPA's RFS2 analysis provides integrated calculations of LUC, which do not distinguish between direct and indirect impacts, while LUC emissions are treated as an additional category in the GREET model. ARB adds the LUC emissions separately. The newest version of GREET (1.8d.1), as well as LEM and GHGenius, allow for detailed inputs of land cover change and the calculation of LUC emissions discussed in Section 5. So far the GREET model only calculates LUC results for corn ethanol.

Differences in WTW Results

CA-GREET, RFS2, LEM and JEC

- CA-GREET, GREET 1.8d, RFS2 and LEM include iLUC so higher overall CI for biofuels.
- EPA RFS2 emphasizes 2022 projection while other studies publish near term results.
- LEM is the only study to include regional N_2O emissions (direct/indirect) and N from soybean biodiesel, JEC includes a N_2O model, GREET N_2O is proportional to applied fertilizer.
- Studies reflect transportation logistics (e.g., JEC soy from Brazil; CA-GREET corn ethanol from Midwest).
- JEC credit for co-product power from biofuel plants is based on displacing biomass power. Other models displace various fossil fuel mixes.
- CA-GREET applies regional detail to electricity mix for corn ethanol.
- Many different methods and valuations of animal feed co-product credit.

The sections below present more disaggregated results for various feedstock/fuel pathways in order to present the differences among WTW models. Examination of the fuel LCA studies reveals the use of a variety of methods (assumptions) for performing the life cycle analysis as well as gaps in the data and differences among model approaches. Details of the differences among models are summarized in Section 2.4. Many of the differences reflect broader fuel LCA issues discussed in Section 4.

The process inputs for most biofuel production processes are well understood for theoretical or generic processes. One key difference among models and studies is the scenario that is examined. The default GREET model inputs represent the U.S. average for corn ethanol. LCFS defaults focus on a range of processes with a set of 2005 baseline parameters. The analysis also includes regional marginal electricity mix and delivery of fuel by truck to blending terminals. The BESS model examines new dry mill corn ethanol plants, while the EPA's RFS2 analysis is based on a projected mix of technologies focusing on 2022. Both the EPA and JEC estimate marginal fertilizer inputs.

Table 2.5. WTW GHG Emissions in Life Cycle Analysis Studies (g CO_2e/MJ fuel)

Fuel (Feedstock)	GREET 1.8c	CA-GREET/ LCFS	JEC[c]	LEM	GHGenius
Gasoline WTT	18	22	13	20	24
Fuel, Vehicle	73	73	73	73	73
Diesel WTT	17	21	14	17	20
Fuel, Vehicle	74	73	73	73	73
CNG WTT	11	12	20	12	10
Fuel, Vehicle	55	55	55	55	55
Ethanol WTT (Corn)	70	69	NA	85	47
Ethanol WTT (Wheat)	NA	NA	61	NA	35
LUC[b]	0	30	NA		0
Fuel, Vehicle	0.8	0.8	0.8	0.8	0.8
Ethanol WTT (Sugarcane)	26	27.4	13	NA	23
LUC	0	46	NF		0
Fuel, Vehicle	0.8	0.8	0.8	0.8	0.8
Ethanol WTT (Farmed Trees)	2	2.4	22	NA	NA
LUC[a]	-15.5	TBD	NA		0
Fuel, Vehicle	0.8	0.8	0.8	0.8	0.8
Biodiesel WTT (Soy)	22	16.8	73	125	16
LUC	0	62	NA		0
Fuel, Vehicle	0.8	4.45	0.8	0.8	0.8
H_2, compressed, (NG)[b]	107	98	105	99	104
Electricity (Avg.)[b]	210	124	130	NA	NA

Disaggregated model results are shown in Appendix A. Note that many process configurations are available in the models and studies. CNG = Compressed Natural Gas; H_2 = Hydrogen Gas; NG = Natural Gas; NA=Not assessed in the LCA model or not found in the available documentation, TBD= to be determined. LCFS pathway for ethanol from farmed trees is not adopted by ARB.

[a] GREET 1.8.c includes estimates of U.S. LUC. For farmed trees and herbaceous biomass the inputs reflect carbon stored in the roots.

[b] Before correction for greater vehicle efficiency.

[c] BioGrace WTT + fuel carbon results in g /MJ: diesel 83.8, corn ethanol 43.6, wheat ethanol 44.3, sugarcane ethanol 24.3, soy biodiesel 57.2, rapeseed biodiesel 52.0.

2.3.1. Petroleum Fuels

Petroleum fuels are typically the reference baseline for transportation fuel LCA studies. Fuel LCA models are generally configured to compare alternative fuels for light-duty vehicles (LDVs) to a gasoline fuel baseline. Gasoline and petroleum diesel fuel are also treated as the baseline fuels for all spark ignition and compression ignition engines respectively. Diesel fuel, and to a lesser extent gasoline, are also components in the production of many biofuels.[9]

[9] Diesel fuel represents less than 0.1 J/J of the energy input into most fuel cycles. For example, a 5 g/MJ difference between diesel results × 0.1 J/J would result in a 0.5 J/J difference in WTT results.

Energy inputs and GHG emissions differ among fuel LCA studies as illustrated in Figure 2.4. Most of the studies listed in the figure use a simple representation of the petroleum fuel pathways. The differences among the LCA models and studies include not only regional differences in crude oil properties, transport distances, and refinery configuration, but also differences in each model's approach.

The JEC and Jacobs studies both model oil refineries. Interestingly, these detailed analyses span the range of refinery emission estimates with the JEC approach resulting in lower emissions due to European refinery configurations and the linear programming approach to determining the effects of marginal fuel production. The Jacobs approach counts emissions associated with petroleum coke and other selected refinery co-products. GREET uses a simpler approach, combining aggregate refinery statistics with estimates of the energy intensity to refine products.

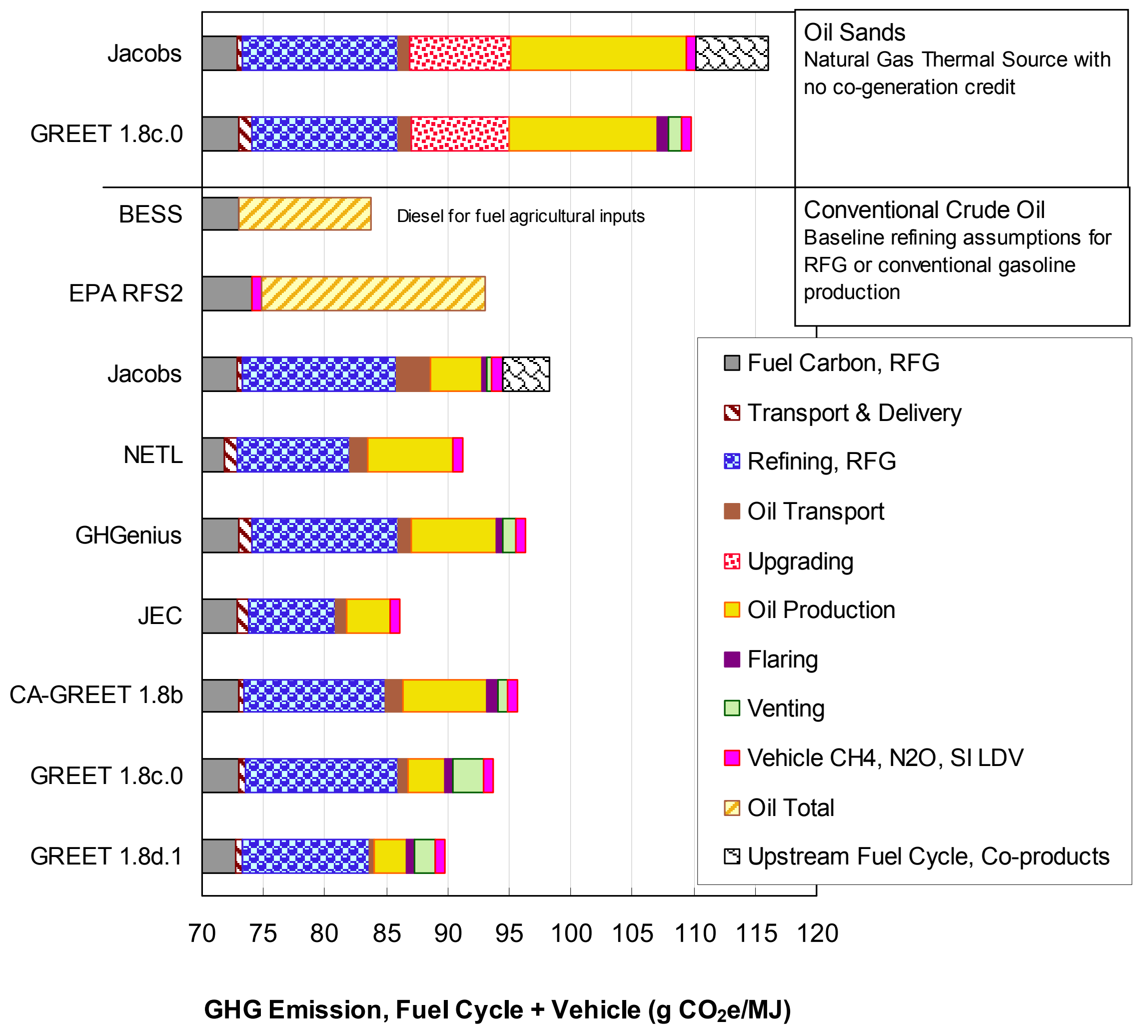


Figure 2.4. GHG Emissions from Gasoline Blendstock[10]

[10] Results for CARBOB for GREET and CA-GREET, Jacobs results for Oil Sands SAGD Coker and Arab Medium. GREET results for Oil Sands SAGD and U.S. Average petroleum. Jacobs study tracks upstream fuel cycle for natural gas and electricity inputs separately. Effect of co-products is about 1 g/MJ.

The approach for crude oil production also varies among studies with both government survey data and modeling approaches. GREET makes use of Department of Commerce statistics for U.S. oil production. The Jacobs study models different crude oil production techniques based on the reservoir type and crude oil properties. The details of the approach for various models are discussed below. The RFS2 and LCFS estimates are based on adaptations to the GREET model.

GREET (1.8c.0, 1.8d)

- Crude oil production inputs based on Department of Commerce survey data for U.S. oil production.
- Associated gas venting and flaring based on DOE Energy Information Agency (EIA) data with an assumed 2:1 ratio of international to U.S. emissions.
- Refining efficiency is assigned to different refinery products on a process allocation basis based on EIA data for petroleum production (Wang 2004). Estimates of refining intensity for each product are converted to a refining efficiency of 88%. ANL calculates refinery efficiency for transport fuels to be only 83.3%, but uses the higher efficiency result that distributes emissions to all products including residual oil and coke.
- Calculation method assigns 1.0 J crude oil to 1.0 J gasoline with additional crude oil added to refining step.

EPA RFS2

- Uses GREET results with adjustments based on the NETL study.
- Results are for 2005 baseline per requirements in the Energy Independence and Security Act (EISA) legislation.

CA-GREET for California

- The California crude mix consists of crude oil from several regions and countries, the most important being: California, Alaska, Saudi Arabia, Ecuador, Iraq, and Brazil. GHG results differ due to transport distance and natural gas flaring.
- California reformulated gasoline blendstock for oxygenate blending (CARBOB) with an estimated refinery efficiency value of 84.5% that takes into account additional hydrogen for CARBOB production and pentane removal[11].
- Ultra Low Sulfur Diesel (ULSD) has a refinery efficiency value of 86.7%.
- Venting and flaring adjusted based on petroleum resource mix.
- Energy inputs for oil production adjusted to reflect TEOR and cogeneration in California.

JEC

- Data are averages for the basket of European crude oils. Variability in crude oil extraction and processing GHG emissions between different operations and wellheads is reflected in uncertainty analysis.

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[11] Refinery efficiency estimate was based on adjustment to GREET 1.8b inputs. GREET 1.8c inputs show higher refinery efficiency for gasoline.

- Large variability in crude oil transportation GHG emissions for European crude, as some crude oils are transported by ship from the Persian Gulf, some from Africa by ship, and Russian and some Middle Eastern crude oils by pipeline to Europe. The figures given are for marginal crude from the Middle East.
- Fuel transport assumes equal distances of water (inland or sea), rail, and pipeline transportation, 250 km each. Diesel distribution and dispensing assumes 150 km traveled via tanker truck.
- Refining efficiency based on linear programming (LP) model that calculates energy inputs for up to a 10% change in refinery gasoline or diesel output from a base case. Only gasoline or diesel outputs are changed. Emissions from liquefied petroleum gas (LPG), coke, and other refined products production are held constant in the LP model approach. Gasoline refining intensity is less than that of diesel because European refineries are configured to produce a relatively higher fraction of diesel to gasoline. Thus, producing more gasoline is less energy intensive than producing more diesel.

Jacobs Consultancy (for AERI)

- Calculates energy inputs and emissions from various crude oil and oil sands options.
- Crude oil production modeled based on oil field parameters (reservoir depth, water/oil ratio, water flooding, gas injection, thermal oil recovery, and flaring).
- Refinery emissions based on Petrol Plan refinery model. Model accounts for crude oil properties and predicts energy inputs and yields from refinery units.
- Energy flows in refinery are assigned to refined products and GHG emissions are tracked though each refinery unit.
- Upstream fuel cycle emissions for natural gas, electricity, and petroleum are tracked separately from direct emissions.
- Petroleum coke and LPG are treated as co-products with substitute values of coal for electric power generation and natural gas derived LPG[12].

NETL

- Detailed evaluation of crude oil production and refining. Not reviewed in detail.

EU Renewable Directive

- Default for petroleum fuels based on JEC study. Not reviewed in detail.

BESS

- Uses diesel fuel as input to corn production and transport. Emission accounting excludes (Version 3.1) upstream emission burdens associated with process fuels (natural gas, diesel, etc.).

[12] The inputs and calculations of co-product credits in this study are lumped together and could be presented in a more disaggregated manner.

The input parameters for the petroleum fuel LCA are presented in Table 2.6 (the key inputs, based on their contribution to the pathway CI, are **bolded**). The analysis of petroleum production includes several gaps. The analyses of refinery emissions are generally conducted based on a limited set of data on oil refining. Modeling of refinery performance and further interpretation would help address the impact of crude oil type. Data on oil production emissions, including the mix of crude oil types and properties, aggregation by country, traded name[13], production technology, and extent of venting and flaring, are needed.

Table 2.6. Petroleum Production Input Parameters

Crude Oil Extraction/Recovery				
Recovery Inputs	**Crude oil Extraction energy**	**Thermal production Energy Source**	**CH_4 flaring**	CH_4 loss
Crude Oil Transport				
Marine	**Distance**	Ship capacity		
Pipeline	Distance	Energy Intensity	Fuel	
Refining				
Refining Energy	**"Efficiency"** cogeneration	**Co-product allocation**	**Crude oil allocation to product**	H_2 input
Vehicle Emissions				
Fossil CO_2 in fuel	Energy Content	Carbon Content		
Vehicle CH_4, N_2O	Emission factors (EFs)	Fuel Economy (mpg)		
Fuel Life Cycle Issues: • Crude oil flaring, water/oil ratio, production inputs • Refinery efficiency and allocation to products • Distribution of crude oil energy inputs to products				

2.3.2. Compressed Natural Gas

Compressed natural gas (CNG) fuel pathways include field collection and pipeline transport to a processing facility, processing, transport to a storage/distribution center, storage, distribution to fueling stations, compression for vehicle fueling, and vehicle combustion. In the production phase, raw natural gas is extracted from oil fields (associated gas), natural gas fields (non-associated), or from coal beds (coal-bed methane). The raw gas is transported by pipeline to a processing facility where liquids such as natural gasoline, propane, and butane are separated from the feed stream; and impurities such as sulfur, mercury, nitrogen, and carbon dioxide are removed. Gas processing protects pipelines and compressors and also ensures that the composition meets specifications. After cleaning the raw gas to pipeline specifications, the natural gas is transported by pipeline for industrial and residential applications. Fuel LCA models use the same pathway for natural gas supply for industrial gas for biorefineries and CNG for vehicle fueling. LCA models add additional energy required for compression and also

[13] Such as Saudi Light or West Texas Intermediate.

examine additional delivery and compression modes. The LCA model input parameters for CNG are presented in Table 2.7 (the key inputs, based on their contribution to the pathway CI, are **bolded**).

Table 2.7. Compressed Natural Gas Input Parameters

Natural Gas Recovery and Pipeline Transport			
Recovery Inputs	**NG**	**Electricity**	**Loss Rate**
NG Processing			
Processing Inputs	**NG**	**Electricity**	**Loss Rate**
Pipeline Gas Transport			
Pipeline	Distance	Energy Intensity	
Natural Gas Compression			
Compression Inputs	**Natural Gas**	**Electricity**	
Vehicle Emissions			
Fossil CO_2 in fuel	Energy Content	Carbon Content	
Vehicle CH_4, N_2O	EFs	Fuel Economy	

The CNG fuel cycle assessment results are presented in Figure 2.5. As the figure shows, natural gas combustion comprises most of the fuel cycle emissions, while natural gas extraction and processing also contribute modestly to emissions.

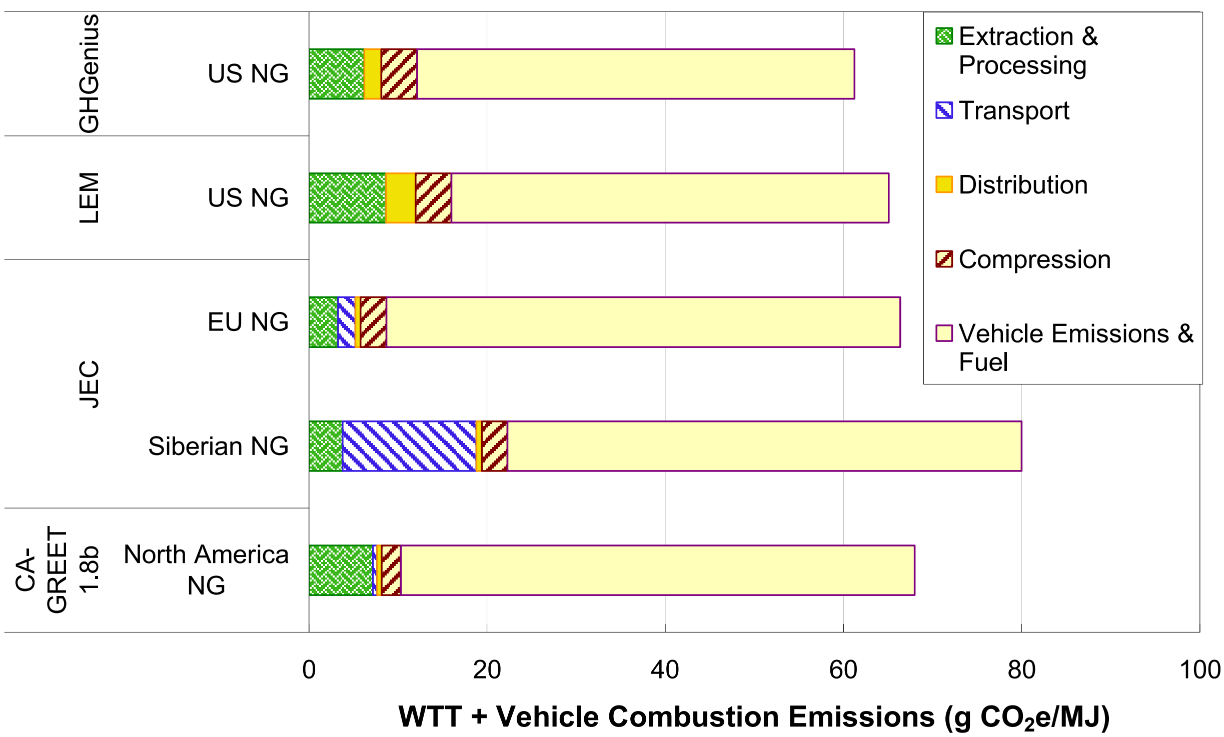

Figure 2.5. GHG Emissions from Compressed Natural Gas

Natural gas is the main input to fertilizer production and process heat for biorefineries and the life cycle component of uncompressed natural gas is equal to the CNG pathway results without

compression. The JEC Siberian NG pathway shows the effect of natural gas transport over long distances (e.g., 7,000 km).
The energy inputs and uncertainties for natural gas production are not examined as thoroughly as those for other fuel pathways in the LCA models. Considerable uncertainties are associated with natural gas loss rates throughout the fuel pathways. Some of these differences are reflected in the default GREET and CA-GREET models. The CA-GREET inputs reflect lower CH_4 leaks in the distribution system than the GREET default. These differences are due to assumptions regarding the fate of unaccounted fuel, or the difference between the amount of gas produced for vehicle fuel and the amount used as fuel. The differences can be due to leaks, metering error, theft, and other factors. Table 2.8 outlines some of the differences among the models/studies considered for CNG.

Table 2.8. Compressed Natural Gas LCA Model Details

Model/Study	Model Assumptions
GREET	• North American natural gas. EIA and EPA statistics used to estimate CH_4 leaks. • CA-GREET data adjusted to reflect lower levels of leaks from pipeline system based on studies of unaccounted for fuel. • Remote natural gas imported as liquefied natural gas (LNG). Liquefier energy inputs based on large scale systems. No calculation of LNG-fired regasification for pipeline gas. • A 98% CNG compression efficiency (0.6 kWh/100 scf).
JEC	• EU mix for natural gas • Natural gas from Western Siberia with higher leak rates • Natural gas from Middle East or Southwestern Asia • Remote LNG • A 98% CNG compression efficiency
LEM	• U.S. natural gas data • Includes natural gas representations of additional countries
GHGenius	• U.S. natural gas data with Canada NG recovery parameters
Fuel Life Cycle Issues: • Natural gas source and gas quality (carbon dioxide removal and venting) • Processing and compression efficiencies • Transport modes and gas losses for each transport mode	

The analysis of natural gas for CNG and biorefinery fuel includes several gaps. Estimates of CH_4 leaks within the U.S. vary between the CA-GREET and the GREET model used by the EPA. Fugitive CH_4 from unconventional sources, such as fractured shale, are not well quantified. Emissions associated with gas production outside the U.S. are assumed to be comparable to emission rates in the U.S. for lack of better data. The basis for the emission factors and effect of equipment type and maintenance need to be examined. Also, the variability in gas composition and effect on CO_2 emissions from gas processing should be considered in uncertainty analyses.

The calculation of natural gas processing emissions provides the opportunity for many errors in fuel LCA calculations due to the myriad units of measure. Some of the common contributions to calculation errors include:

- Units of commerce for natural gas are standard cubic feed (scf) and therms or 100,000 Btu, HHV with 1030 Btu/scf.
- Fuel LCA calculations are on an LHV basis with 930 Btu/scf.
- Reference temperature for gas commerce in the U.S. is 65°F, which is often confused with normal temperature and pressure for scientific measurement of 25°C (77°F) or the reference temperate for hydrogen sales (70°F).
- Gas composition, heating value, and density from different data sources are often combined leading to incorrect GHG calculations.
- CNG is sold in gasoline equivalent gallons. 1 gge = 1.25 therms, which involves several unit conversion steps to relate energy or fuel carbon on a common unit of measure.

2.3.3. Electric Power

Electricity is generated from a wide portfolio of feedstocks including coal, fuel oil, natural gas, nuclear sources, biomass, hydroelectric energy, and other renewables such as wind. Fuel LCA models calculate GHG emissions for a mix of electricity generation resources. The models account for transmission losses and calculate upstream fuel cycle emissions in proportion to the fuel used for each production technology. Power plant emissions depend on fuel efficiency plus emission factors for CH_4 and N_2O.

Each of the models reviewed includes different feedstock mixes, based on the geographic region of interest. The CA-GREET study includes regional consideration for various scenarios. Fuel pathway components are bundled into "feedstock" and "fuel" groups to determine the regional input parameters, including electricity mix. The model is configured with the California average electricity mix for use with the baseline petroleum pathways. A marginal power generation resource mix is associated with new added generation capacity and alternative fuels. JEC estimates emissions for a variety of generation options and based on data from the GEMIS database (Öko 2010).

LEM and GHGenius use a unique electricity mix for many of the fuel pathway types; some fuel pathways are based on the U.S. average (or other country selected) electricity mix. Table 2.9 summarizes the treatment of electricity in the models and studies reviewed.

Table 2.9. Electricity LCA Model Details

Model/Study	Electricity Generation Summary	Natural Gas Generation Efficiency	
		Average	CCGT
GREET 1.8c	• Electricity calculated for resource mix for U.S., CA, U.S. Northeast, and user-defined resource mix. • U.S. average electricity mix used for biofuel production and co-product power in the U.S.	40.1%	53%
CA-GREET	• Fuel pathways under LCFS use one region for feedstock production and transport and one region for fuel production and transport. • CA average is based on Argonne default CA average mix of feedstocks. • CA marginal electricity is based on combined cycle gas turbine (CCGT) electricity subject to the California renewable portfolio standard (RPS) (currently 22% renewables). • Other regions include CA petroleum; Midwest, Southeast Asia with no nuclear or hydro power in marginal resource mix. • Fuel properties for powder river basin coal.	39%	51.8%
JEC	• EU electricity mix for feedstock and fuel production in Europe. • Energy efficiency and resource mix based on GEMIS data base.	35.4%	51%
LEM	• Electricity mix based on selected generation resource for each fuel technology (starch ethanol, U.S. electric vehicle mix, etc.). • No explicit CA or U.S. regional electricity mixes. • U.S. generation efficiency calculated from EIA data and AEO projections.	44%[a]	NF
GHGenius	• Average Canada resource mix based on Statistics Canada data from the National Energy Board.	36%	51%

[a] 31.3% in 1970, 35.6% in 2010, NF=not found in documentation or model

The fuel cycle results per MJ of delivered electricity are shown below in Figure 2.6. The figure shows that the results for fossil fuel-derived feedstocks range from approximately 100 to over 300 g CO_2e/MJ electricity delivered. Projections for power generation efficiency result in a significant variation among the model predictions, especially in future years. The projections for future improvements in generation efficiency vary considerably among models. Estimates of fuel properties as well as the upstream fuel cycle for natural gas and coal production contribute to the difference. Another difference among models is the representation of marginal generation resource. For CA-GREET, the marginal resource mix varies by region. The impact of electricity mix is apparent when comparing ethanol plants operating in California compared to the Midwest. The difference in CI is about 3 g/MJ. The default GREET model and the EPA's RFS2 analysis does not reflect these regional differences.

Renewable feedstocks contain biogenic carbon, therefore only the combustion methane and nitrous oxide emissions are considered. The carbon neutral assumption results in a much lower GHG estimate for fossil fuel-derived electricity. Most biomass power is produced from residue, which is the basis for calculation in the GREET model.

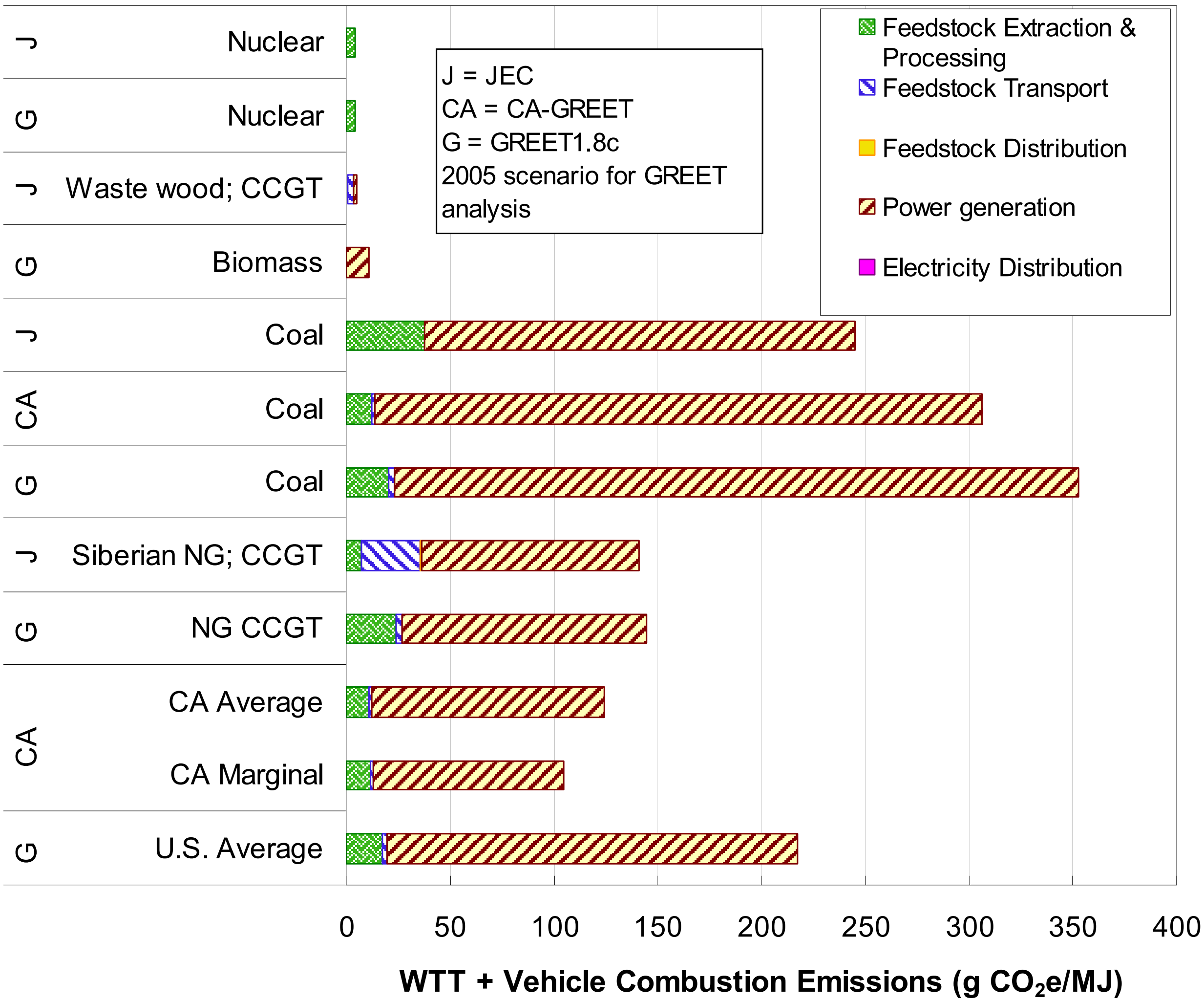

Figure 2.6. GHG Emissions for Transportation Electricity (g CO_2e/MJ before introducing vehicle efficiency)

Several issues occur in the treatment of electric power for LCA. First, the estimates for generation efficiency vary considerably among fuel LCA models for comparable equipment, such as combined cycle gas turbines (CCGT). These differences reflect variations in assumptions rather than regionally-specific data. Also, no uniformly agreed upon method exists for defining a marginal electricity resource mix. For example, an assumption for marginal resource mix might be 100% natural gas CCGT. Short term generation on the margin can be predicted with dispatch models (McCarthy 2010, Unnasch 2001). Alternatively, an estimate for long term capacity expansion may be factored into the analysis. The analyses of power generation could also be based on energy models that take into account resource shift in energy markets in the same manner as LUC models assess the use of agricultural commodities.

Even the calculation of average GHG emissions is problematic. GHG emissions from electric power generation are well-documented as part of emission inventory efforts. Emission inventories in the U.S. are collected through the EPA's eGRID database (EPA 2008), with measurements based on direct CO_2 emissions or fuel using IPCC GHG calculations methods. The average emissions from power generation are estimated from reported power sales and GHG emissions. Fuel LCA models are populated with estimates of generation efficiency[14] to calculate GHG emissions. The average GHG emissions for power generation, in GREET for example, are not periodically validated against emissions inventories. The efficiency inputs for the combination of power generation resources could be adjusted to achieve agreement from the inventory.

Another issue applies to fuel LCA calculations that use external inputs of life cycle results (such as BESS, as well as many LCA studies). Emissions associated with electric power are often based on the reported average power generation intensity for a region, which does not include upstream fuel cycle emissions. In such cases, the WTW energy inputs for electric power are incorrectly represented.

2.3.4. Hydrogen

Hydrogen is a component of many fuel production pathways and is also a potential fuel for transportation applications. Fuel LCA models calculate the energy inputs and emissions for existing hydrogen technologies as well as future low GHG hydrogen technologies. For industrial applications, hydrogen is primarily produced via steam methane reformation (SMR) of North American natural gas in the U.S. SMR-based hydrogen production is a component of hydrogen vehicle pathways and also serves as a feedstock for oil sands upgrading, oil refining, vegetable oil hydrotreating, and other fuel processing steps[15]. Hydrogen is used for fuel processing steps such as sulfur removal and cracking the fuel into components with a higher hydrogen-to-carbon ratio. In the case of vegetable oil processing, hydrogen input is about 3% of the mass of the feedstock oil[16], which translates into 0.08 kg/gal of fuel. Hydrogen input reflects about 8% of the primary energy in this case.

For natural gas SMR systems, the feedstock is recovered and transported to a hydrogen plant (either at a central location or hydrogen fueling station). There, high temperature steam is reacted with the methane to produce carbon monoxide (CO) and hydrogen; this process is highly endothermic. The CO further reacts with water in the exothermic water gas shift reaction to yield more hydrogen and carbon dioxide. The input parameters for natural gas-based hydrogen are presented in Table 2.10 (key inputs are **bolded**).

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[14] This criticism does not apply the JEC analysis, where the data are based on the GEMIS inventory model.
[15] Fuel LCA models typically use the calculation for uncompressed hydrogen as the input for other fuel processing steps.
[16] GREET default for renewable diesel II pathway.

Table 2.10. Natural Gas-Based Hydrogen Input Parameters

Natural Gas Recovery and Pipeline Transport			
Recovery Inputs	**NG use**	**Electricity**	**Loss Rate**
NG Processing			
Processing Inputs	**NG use**	**Electricity**	**Loss Rate**
Pipeline Gas Transport			
Pipeline	Distance	Energy Intensity	
Hydrogen Production			
Reformer Inputs	**Natural Gas**	**Electricity**	
Reformer Performance	**Efficiency**		
Liquefaction Inputs	**Natural Gas**	**Electricity**	
Liquefier Performance	**Efficiency**		
Liquid Hydrogen T&D			
Heavy-Duty Truck	Distance	Capacity	Fuel Economy

Table 2.11 summarizes the treatment of hydrogen in the models and studies reviewed. The hydrogen pathways produce no co-products other than steam. A steam credit is applied to hydrogen production as a model input. Hydrogen plants that are integrated with oil refineries provide some of their excess steam as process heat to other refinery processes.

The hydrogen fuel cycle results are presented in Figure 2.7. Production emissions correspond primarily to the carbon in the feedstock, which is ultimately converted to CO_2. Compression and liquefaction emissions contribute a significant fraction for hydrogen fueled vehicles. However, hydrogen used for fuel processing typically does not require these steps.

Some elements of hydrogen vehicle infrastructure carry over to calculations in fuel LCA models. For example, one version of the GREET model includes a 700 mi pipeline for hydrogen transport for all applications, including oil sands upgrading. In practice, this hydrogen is produced on-site. Such shortcuts are difficult to avoid in a spreadsheet model where each fuel pathway is an active calculation.

The CA-GREET results shown demonstrate the range in emissions, from central production with liquefied hydrogen transport by truck to distributed production with compression. The results shown for JEC, LEM, and GHGenius exclude a liquefaction step. GHG emissions are comparable for similar fuel pathways because the emissions are primarily a function of the natural gas fuel cycle results with similar conversion efficiency assumptions.

Even though hydrogen production from natural gas is an established technology, a number of gaps remain in the life cycle analysis. The default assumptions for fuel LCA models reflect a combination of projections and data. The actual data for hydrogen production systems requires further validation. In addition, data inputs and the application to conventional fuel pathways for hydrogen compression and distribution, as well as CH_4 emissions from reformer furnaces, remain uncertain.

Table 2.11. Hydrogen Production LCA Model Details

Model/Study	Feedstock Efficiency	Technology Assumptions
GREET LEM	69.5%	• Efficiency for hydrogen based on projected improvement over 1990 estimate of 68% efficiency. • Central hydrogen pathway includes 300 mi pipeline delivery. • 83% tube-side efficiency of natural gas to hydrogen • Option for steam credit. • LEM inputs comparable to GREET defaults. • GREET CH_4 and N_2O emission factors based on natural gas. combustion. CA-GREET, data from reformer furnace source test.
JEC	70%	• Approach comparable to GREET, range of natural gas sources
Jacobs	65%	• Data for natural gas SMR at oil refinery

Fuel Life Cycle Issues:

- Natural gas source
- Hydrogen fuel pathway structure (central vs. onsite, delivery mode, etc.)
- Hydrogen plant efficiency
- Carbon dioxide sequestration from steam methane reformer
- Feedstock efficiency refers to hydrogen energy/natural gas feedstock

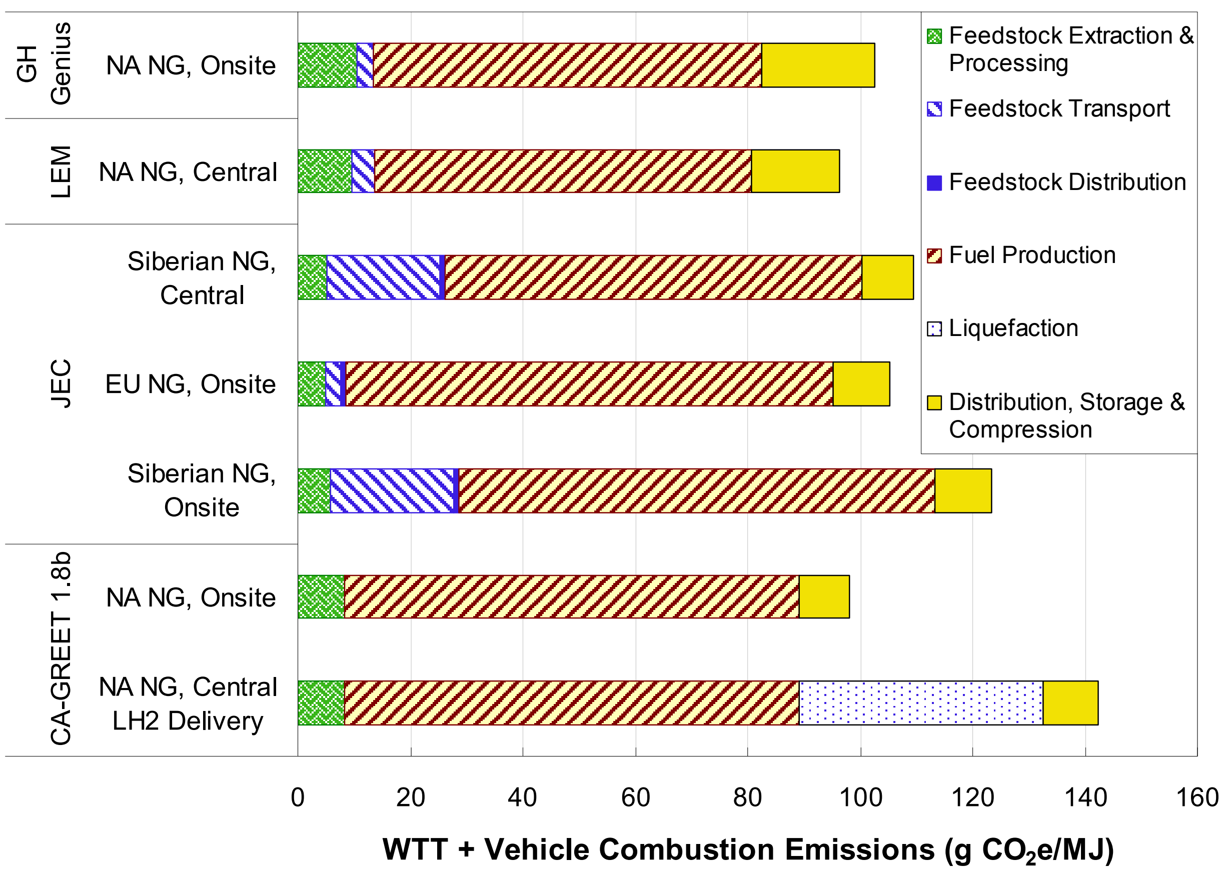

Figure 2.7. GHG Emissions from Compressed Hydrogen (not adjusted for vehicle efficiency)

2.3.5. Biofuels

This section summarizes the key assumptions and issues associated with the life cycle analysis of biofuels and presents the greenhouse gas emission results for selected pathways in the models/studies reviewed:

- Ethanol
    - Corn/wheat ethanol
    - Sugarcane ethanol
    - Cellulosic ethanol
- Biodiesel
- Renewable diesel

The models and studies reviewed and relevant results are presented and discussed further in the following subsections.

2.3.5.1. Corn/Wheat Ethanol

Ethanol from corn or other grains is produced by hydrolysis of the starch to sugar, fermentation of the resulting sugar to ethanol, and distillation of the fermentation product to yield fuel grade ethanol. The fuel pathway inputs for Midwest corn ethanol are given in Table 2.12, which shows the key inputs in **bold**. The agricultural chemical inputs shown include the fertilizer nitrogen (N), phosphorus (P), potassium (K), and lime content. The farming and feedstock transport input types are the same for all agricultural feedstocks. Fuel production results depend on the process fuel used (e.g., coal, natural gas, stover) and electricity use and product yields. Ethanol transport results are primarily a function of the transport distance from the Midwest to the refueling station. Vehicle emissions include only the combustion methane (CH_4) and nitrous oxide (N_2O), since the carbon in the fuel is considered biogenic and omitted from the analyses. The net carbon flux associated with biogenic uptake is addressed through LUC emissions (see Section 4.24).

Table 2.13 summarizes the treatment of corn and wheat ethanol in the models and studies reviewed. All of the studies model dry mill corn ethanol similarly and treat the dry distiller's grains and solubles (DDGS) co-product using the displacement method, although the method for applying the credit varies. The GREET model, the JEC study, LEM, and GHGenius assume that DDGS displaces feed corn and soybeans (or soybean meal). The CA-GREET inputs were modified to reflect 1:1 feed corn displacement without soybean meal displacement. This assumption is also consistent with the displaced feed assumed in the GTAP model (Section 5). This choice removes the dependence of corn ethanol fuel cycle results on the soybean biodiesel calculations and avoids the need for a displacement factor to equate feed corn and soybeans—two very different feeds with different nutritional profiles. CA-GREET also evaluates wet mill corn ethanol and assumes the corn gluten feed (CGF) and the corn gluten meal (CGM) displace feed corn.

The starch-to-ethanol fuel cycle results are presented in Figure 2.8. As the results demonstrate, feedstock and fuel production yield the highest emission shares. Feedstock and fuel transport are responsible for only a small share of emissions. Biogenic fuel is treated as zero net $CO_{2,}$ thus vehicle fuel combustion contributes 0.8 g CO_2e/MJ from CH_4 and N_2O emissions to the total fuel cycle.

Table 2.12. Corn Ethanol Input Parameters

Farming					
Farming Energy	**Diesel**	**Gasoline**	**NG**	**LPG**	Electricity
Fertilizers	**N, N Share**	**N_2O Rate**	P	K	Lime
Pesticides	Herbicides	Insecticides			
Corn Transport					
Medium-Duty Truck	Distance	Capacity	Fuel Economy		
Heavy-Duty Truck	Distance	Capacity	Fuel Economy		
Ethanol Production					
Production Inputs	Natural Gas	Electricity			
Plant Performance	**Ethanol Yield**	DDGS Yield			
Ethanol T&D					
Heavy-Duty Truck	**Distance**	Capacity	Fuel Economy		
Rail	Distance	Capacity	Energy Intensity		
Heavy-Duty Truck	Distance	Capacity	Fuel Economy		
Vehicle Emissions					
Vehicle CH_4, N_2O	EFs	Fuel Economy			

Table 2.13. Corn and Wheat Ethanol LCA Model Details

Model/Study	Feedstock	Technology	Ethanol Production and Co-products
GREET	• U.S. Corn • NASS data for ag inputs, future projections	• Dry mill • Wet mill	• Option for allocation and substitution of DGS • Wet mill: CGF and CGM displace feed corn and N in urea and corn oil displaces soybean oil • Detailed calculations of feed substitution in GREET 1.8d based on use of animal feed (poultry, swine, etc.)
CA-GREET/ LCFS	• U.S. Corn	• 10 separate sub-pathways for current technology	• Dry mill: DGS displaces feed corn (1:1 mass basis) • GREET defaults for ag inputs
EPA RFS2	• Corn/Agro-economic model predictions	• Projection of technology mix through 2022	• Ethanol plant impacts based on GREET with assumed efficiency improvements • Agricultural inputs based on FASOM
JEC	• EU Wheat/ marginal fertilizer inputs	Hydrolysis and fermentation	• DDGS co-product is assumed to either replace animal feed or used as co-fuel in a coal fired power plant
EU Renewable Directive	• EU Maize	• Hydrolysis and fermentation	• Credit for DGS is based on energy allocation
LEM	• Corn	• Dry mill	• DDGS displaces feed corn and soybeans
GHGenius	• Corn • Wheat	• Dry mill • Wheat: hydrolysis and fermentation	• DDGS displaces feed corn and soybeans

Fuel Life Cycle Issues:

- Corn farming and nitrogen impacts (Section 4).
- Share of nitrogen input from manure and rotational cropping with soybeans.
- DDGS drying.
- Animal feed displaced by DGS. Variability in value of DGS such as high protein DGS.
- Various co-product methods.
- Production of both ethanol and corn oil. Corn oil used for food or biofuel feedstock.
- Natural gas or coal required for fermentation and distillation.
- Truck hauling to blending rack and retail station (Truck haul to blending is included in CA GREET but omitted from most other fuel LCA models). The GHG impact is small. However other life cycle impacts such as criteria pollutant emissions are calculated from fuel LCA models.

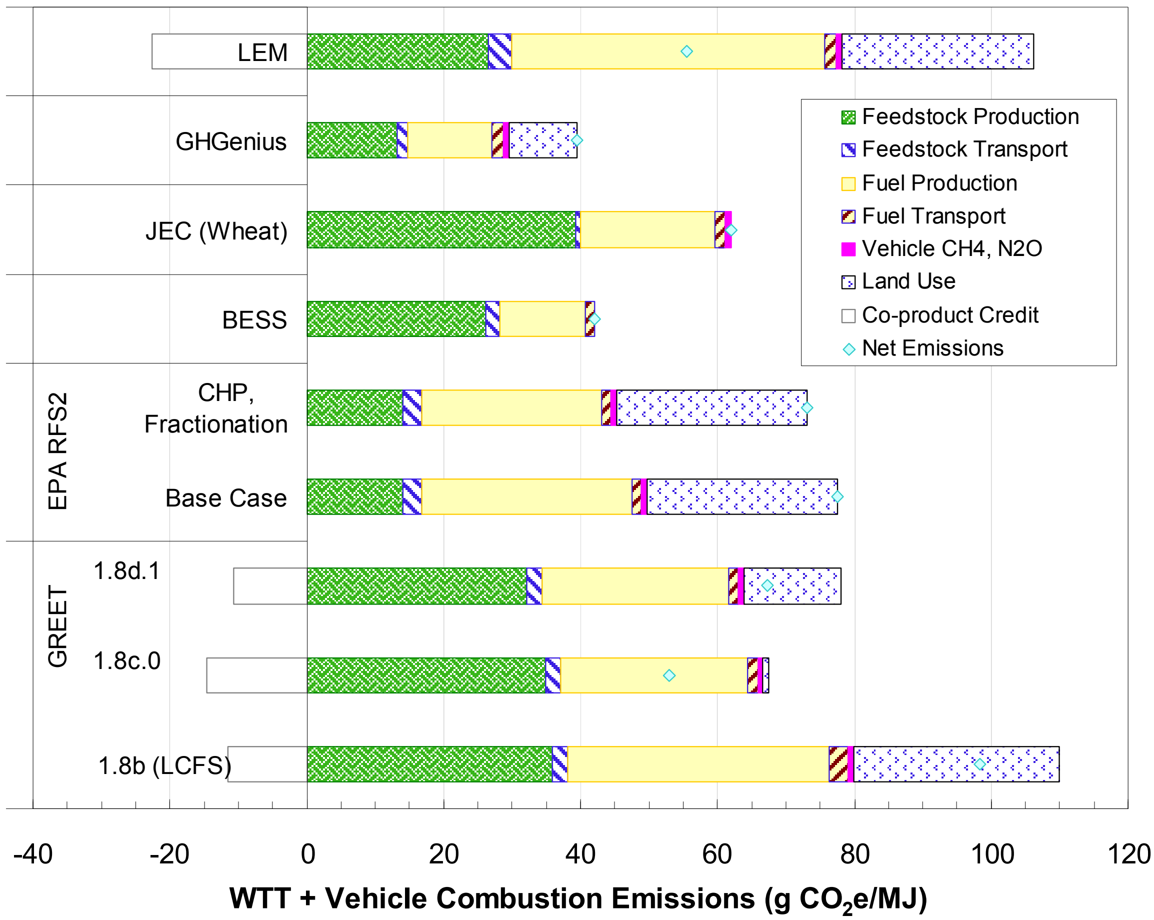

Figure 2.8. GHG Emissions from Corn and Wheat Ethanol[17]

2.3.5.2. Sugarcane Ethanol

Ethanol is produced from many sugar crops, including sugarcane, sweet sorghum, and sugar beets. Ethanol from sugar crops is produced via fermentation of the sugar in the feedstock. For sugarcane, the raw cane is cultivated on a sugar plantation and then transported to an ethanol plant where the sugar-rich cane juices are extracted and fermented. The fermentation is similar to corn ethanol fermentation after the corn starch has been hydrolyzed to sugars. The resulting "beer" (fermentation product) is then distilled and dehydrated to fuel quality purity and transported to a blending facility, followed by blend transportation to a fueling station. This section focuses on the inputs and life cycle results for Brazilian sugarcane ethanol discussed in the studies reviewed.

[17] Results from fuel LCA models or reports. Co-product results are lumped with feedstock production for BESS, GHGenius, JEC, and RFS2. LCFS result is for average Midwest ethanol. RFS2 result shown here is for dry mill with DDGS without advanced technology configurations.

Analyzing the sugarcane ethanol fuel pathway requires defining approximately 30 to 40 inputs, eight of which are key parameters that drive the life cycle CI results. Input parameters for ethanol produced from sugarcane are listed in Table 2.14; key inputs based on their contribution to the pathway CI are shown in **bold**.

Table 2.15 summarizes the treatment of Brazilian sugarcane ethanol in the models and studies reviewed. Only the CA-GREET and JEC studies are noted in the table because both LEM and GHGenius do not consider sugarcane ethanol pathways.

Table 2.14. Sugarcane Ethanol Input Parameters

Farming					
Farming Energy	**Diesel**	**Gasoline**	**NG**	**LPG**	Electricity
Fertilizers	**N, type**	**N_2O Rate**	P	K	Lime
Farming	Field burning **CH_4**	Farm energy inputs			
Pesticides					
Sugarcane Transport					
Heavy-Duty Truck	Distance	Capacity	Fuel Economy		
Ethanol Production					
Production Inputs	**Dehydration fuel mix**	Bagasse	Oil (lubricant)		
Plant Performance	**Co-product power**	**Ethanol Yield**			
Ethanol T&D					
Heavy-Duty Truck	Distance	Capacity	Fuel Economy		
Pipeline	**Availability**				
Ocean Tanker	**Back haul**	Distance	Capacity		
Heavy-Duty Truck	Distance	Capacity	Fuel Economy		
Vehicle Emissions					
Vehicle CH_4, N_2O	EFs	Fuel Economy			

Table 2.15. Sugarcane Ethanol LCA Model Details

Model/Study	Feedstock	Technology Scenario	Process Energy and Co-products
GREET	• Brazilian sugarcane	• Inputs for straw burning or mechanical harvest, (more diesel, less CH_4), co-product electric power credit	• Excess bagasse combusted to generate electricity and displace assumed natural gas marginal mix • Bagasse is treated as carbon neutral so only CH_4 and N_2O emissions contribute as GHG emissions
LCFS	• Brazilian sugarcane	• Straw burning and mechanical harvest considered	
RFS2	• Brazilian sugarcane	• Same treatment as GREET	• Same treatment as GREET
JEC	• Brazilian sugarcane	• Scenarios for straw burning for harvest • Straw burning harvest and excess bagasse co-product credit	• Excess bagasse combusted to generate heat and displace diesel • Bagasse is treated as carbon neutral • Scenarios for displacing biomass fired power
EU Directive	• Brazilian sugarcane	• Based on JEC analysis	• No co-product credit for electric power

Common Assumptions

- Bagasse combustion provides heat source for sugar mill and ethanol plant
- Carbon neutral biomass

Fuel Life Cycle Issues:

- Treatment of co-product power. Significant variability in amount and treatment of co-product power, including displaced grid mix.
- Tanker ship capacity and distance for ballasting haul (cargo capacity impact energy consumption). Chemical tankers generally do not make significant empty (ballasting) hauls although empty backhauls are assumed in the GREET model).
- Variable farm inputs and documentation.
- Harvesting method (field burning vs. mechanical) affects emissions from feedstock production.
- Share of Brazilian ethanol dehydrated using heavy oil in the Caribbean excluded from fuel pathway in GREET. EPA RFS2 examines Caribbean dehydration. Lower processing energy in Brazil and impact on co-product power.
- Vinasse co-product (if used as animal feed or for digester fuel) not examined in life cycle analysis.

Figure 2.9 summarizes fuel cycle results for the studies considered. The treatment of co-product bagasse energy differs between the CA-GREET and JEC approaches. The CA-GREET model assumes the excess bagasse is used to generate electricity, which displaces the Brazilian marginal electricity mix (accounting for transmission losses), which consists entirely of natural gas-fired combustion sources. The quantity of co-product power generated and the credit assigned have a significant effect on the life cycle results. The JEC study considers two sugarcane ethanol scenarios: 1) a scenario with no credit for excess bagasse and 2) a scenario that includes a credit for the excess bagasse not used as process fuel and assumes that the bagasse energy displaces a comparable quantity of diesel heat energy.

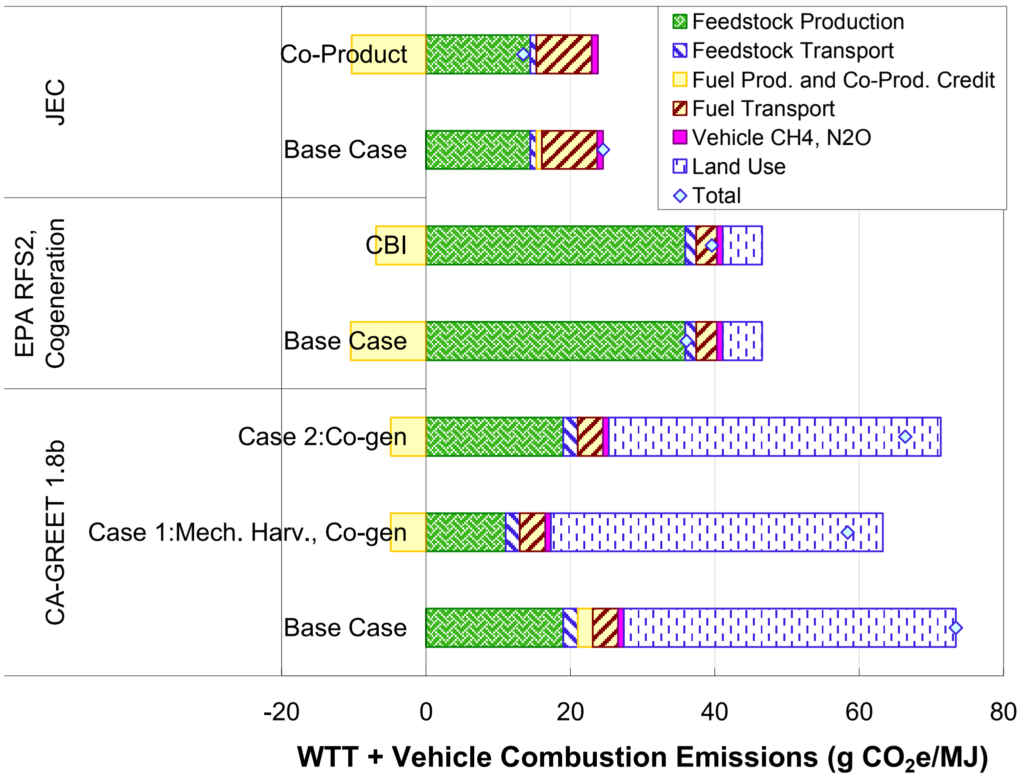

Figure 2.9. GHG Emissions from Brazilian Sugarcane Ethanol[18].

The LCFS calculates CI values for scenarios with mechanized harvesting and cogeneration (ARB 2009b). Mechanized harvesting reduces CH_4 emissions from burning straw in the field. The credit for co-produced power is based on an assumed natural gas resource mix. The treatment of co-produced power differs among models with the JEC observing that bagasse and other biomass could be converted to electric power absent ethanol production (Larivé 2008). With this assumption, the credit for co-produced electric power is almost zero in contrast to the significant credit calculated in the GREET model, which is based on displacing marginal natural gas-based power. The same assumption applies under the RFS2 analysis. This situation represents a significant difference between the treatment of fuels under the EU Directive and the RFS2.

The primary data gaps associated with sugarcane ethanol are associated with the documentation of the myriad configurations of ethanol plants, transport logistics, and fertilizer inputs.

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[18] Results do not include LUC. See Section 5.

2.3.5.3. *Cellulosic Ethanol from Forest Waste and Farmed Biomass:*

Fuel LCA models examine several conversion technologies for cellulosic ethanol production. In the hydrolysis approach, the cellulose and hemicellulose in the biomass are converted to fermentable sugar using enzymes or acids. Unconverted material including lignin is recovered and used to generate process steam and/or electric power. Table 2.16 lists the input parameters associated with cellulosic ethanol production, with the key parameters, based on their contribution to the pathway CI, indicated in **bold** type.

Table 2.16. Cellulosic Ethanol Input Parameters

Biomass Farming or Collection					
Production Energy	**Diesel**	Electricity			
Fertilizers	**N, N Share**	**N_2O Rate**	P	K	Lime
Pesticides	Herbicides	Insecticides			
Feedstock Transport					
Heavy-Duty Truck	Distance	Capacity	Fuel Economy		
Ethanol Production					
Production Inputs	Biomass	Oil (lubricant)	**Electricity Co-product Credit**	Chemical Inputs	
Plant Performance	**Ethanol Yield**	**Export Electricity**			
Ethanol T&D					
Heavy-Duty Truck	Distance	Capacity	Fuel Economy		
Vehicle Emissions					
Vehicle CH_4, N_2O	EFs	Fuel Economy			

Fermentation approaches use one of several saccharification processes, including enzymatic hydrolysis, dilute acid and concentrated acid hydrolysis, and others. While a variety of entities are involved in developing converting cellulosic feedstock into fermentable sugars by various means, fuel life cycle modeling work has focused on the acid enzyme processes. If technically successful, these processes would require fewer material inputs than other technologies. Table 2.17 summarizes the treatment of cellulosic ethanol production in the models and studies reviewed.

Alternatively, synthesis gas from biomass gasification is converted to ethanol via catalytic or biological approaches. Synthesis gas containing CO, CH_4, and other species is partially converted to ethanol and the unreacted constituents are converted to process steam and electric power. Figure 2.10 summarizes fuel cycle results for the studies considered.

The treatment of co-product power differs among various studies and models. The GREET, GHGenius, and LEM models provide a credit for excess electricity exported to the grid. The amount of co-product power produced and its corresponding credit have a significant effect on the life cycle results. JEC provides a credit for the electricity produced based on a wood-fired steam turbine power generation while other models allow for the displacement of grid power. The GREET model approach results in lower GHG emissions for ethanol technologies with lower yields (L ethanol/tonne feedstock) and higher levels of unconverted fuel used for power production.

Table 2.17. Cellulosic Ethanol LCA Model Details

Model/Study	Feedstock	Technology	Co-products
GREET CA-GREET	• Energy crops: 120 MJ/tonne • Forest residue: 650 MJ/tonne	• Enzymatic hydrolysis and fermentation • Gasification with biological conversion of syngas	• Excess electricity displaces U.S. average electricity
RFS2	• FASOM analysis of switch grass	• Enzymatic hydrolysis and fermentation	• Excess electricity input to FASOM with credit for excess generation
JEC	• Energy crops: 118 MJ/tonne • Forest residue: 118 MJ/tonne	• Enzymatic hydrolysis and fermentation	• Power generation from steam and waste water treatment biogas • Excess electricity displaces wood fired power
LEM	• Energy crops	• Enzymatic hydrolysis and fermentation	• Excess electricity displaces U.S. average electricity
GHGenius	• Energy crops	• Enzymatic hydrolysis and fermentation	• Excess electricity displaces Canadian average electricity

Fuel Life Cycle Issues:

- Limited data to support yields, co-product power, and chemicals, which vary with feedstock and technology.
- Treatment of co-product power. JEC assigns effectively no credit to co-product power because the biomass could have been converted to electric power.
- Inputs for acid hydrolysis technologies need to be analyzed.
- Large variability in energy inputs for forest residue collection.
- Impact of crops on soil carbon storage through build up of root mass (Section 5).

In principle, the inputs to calculate the GHG emissions for cellulosic ethanol pathways are straightforward because the biorefinery concept involves the use of biomass residue as process fuel with few additional inputs. Information and analysis gaps for cellulosic pathways include the lack of data or commercial designs for actual plant performance and inputs compared with idealized process designs. The effect of growing feedstocks on soil carbon stocks (Section 5) is also uncertain. For biorefineries that burn lignin residue, the ethanol yield will affect the life cycle of the feedstock. However, lower yields will generally result in more residue available for the co-production of electric power (See Section 4.6). The treatment of co-products such as chemical feedstocks also requires further attention and represents the most significant difference among model approaches.

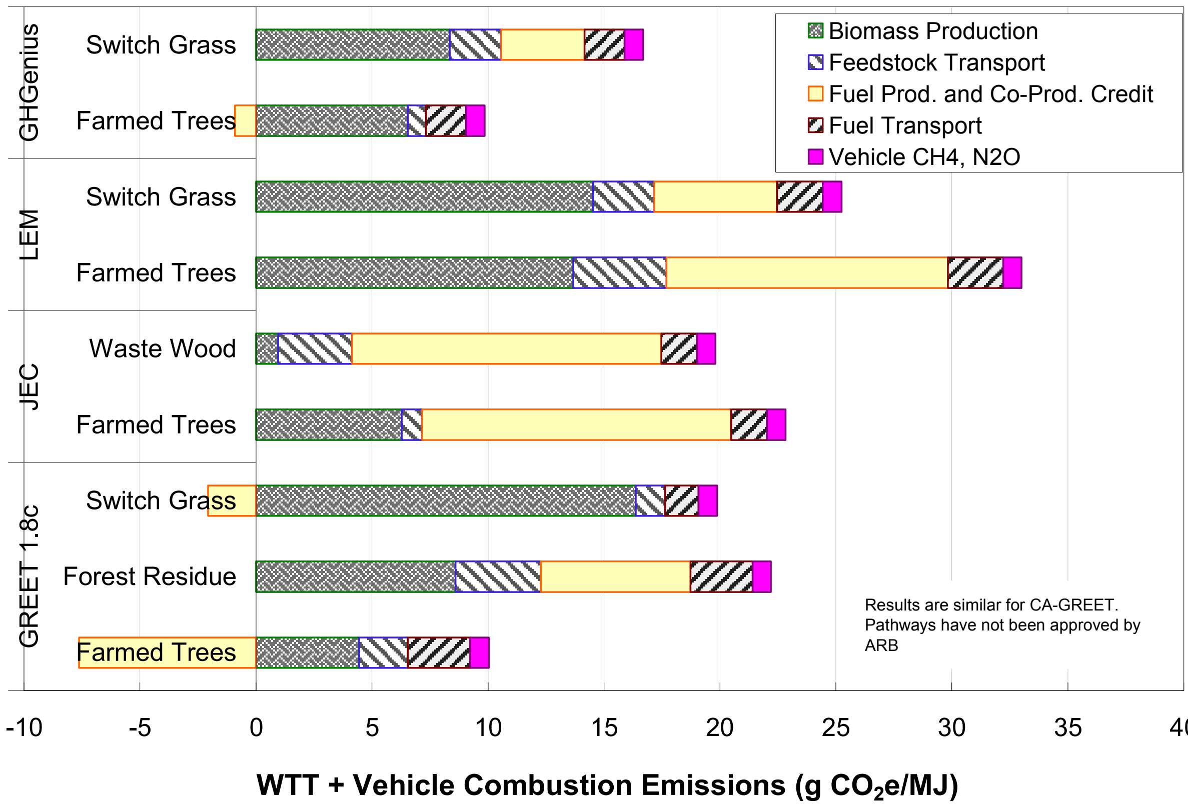


Figure 2.10. GHG Emissions from Cellulosic Ethanol[19]

2.3.5.4. Biodiesel

Many fats and oils provide potential feedstock for biodiesel production. Sources include plant oils, used cooking oil, and animal tallow. The precise energy inputs and conversion reaction conditions depend on the feedstock type, but the general conversion process is the same. This section focuses on inputs and results for biodiesel derived from plant oils. In these processes, oil feedstock comprised of triglycerides is heated and combined with methanol in the presence of a catalyst (acid or base) to produce fatty acid methyl esters (FAME) (biodiesel), along with glycerin as a co-product. A base catalyst (sodium hydroxide) is typically used to catalyze the transesterification. Sodium methoxide is added to facilitate the reaction. Alternatively, triglycerides can be reacted with ethanol to yield a fatty acid ethyl ester (FAEE) biodiesel fuel. Analyzing biodiesel fuel pathways requires defining approximately 30 to 50 inputs, nine to twelve of which are key parameters that drive the life cycle results. Input parameters for biodiesel produced from plant oil are listed in Table 2.18; key inputs are shown in **bold** type.

[19] Estimates of the LUC impact of cellulosic feedstocks are underway.

Table 2.18. Soybean Oil Biodiesel Input Parameters

Farming					
Farming Energy	**Diesel**	**Gasoline**	**NG**	**LPG**	Electricity
Fertilizers	**N, N Share**	**N_2O Rate**	P	K	Lime
Pesticides	Herbicides	Insecticides			
Oil Seed Transport					
Heavy-Duty Truck	Distance	Capacity	Fuel Economy		
Oil Extraction					
Extraction Energy	**NG**	Biomass	Electricity		
Solvent Use	Hexane				
Mill Performance	**Oil Yield**				
Co-Product	**Yield**	**Method**			
Oil Transport					
Heavy-Duty Truck	Distance	Capacity	Fuel Economy		
Transesterification					
Production Inputs	**NG**	Electricity	Methanol	Chemicals	
Plant Performance	**BD Yield**	**Glycerin Yield**			
BD T&D					
Heavy-Duty Truck	Distance	Capacity	Fuel Economy		
Ocean Tanker	Distance	Capacity	Fuel Economy		
Barge	Distance	Capacity	Fuel Economy		
Rail	Distance	Capacity	Energy Intensity		
Vehicle Emissions					
Fossil CO_2 in fuel	**Methanol Input**				
Vehicle CH_4, N_2O	EFs	Fuel Economy			

Table 2.19 summarizes the key results from the CA-GREET and JEC studies for the base case soybean biodiesel cases, and notes differences between them. The major differences between the two analyses arise from differences in the feedstock transport distances (and modes) assumed and the treatment of process co-products.

Table 2.19. Vegetable Oil Biodiesel LCA Model Details

Parameter	Feedstock	Co-products Meal	Glycerin	Carbon in Fuel
GREET	• Soybeans	• Default allocation method. Various hybrid and substitution methods.	• Default allocation method. Various hybrid and substitution methods.	• Zero
RFS2	• Soybeans	• Follows GREET method for energy inputs, CLCA for agricultural inputs	• Credit based on energy content	• Zero
CA-GREET	• Soybeans	• Farming and oil extraction allocated to meal by mass	• Energy allocation	• Includes methanol
JEC	• Brazil soybean (incl. transport) • Rapeseed • Sunflower • Palm oil	• Soybean meal displaces wheat	• Displaces propylene glycol • Purification energy included (2.45 g CO_2/MJ) • Used as biogas • Used as animal feed	• Substitution method, net zero
LEM	• Soybeans	• Substitute credit for feed	• Glycerin is credited as displacing petro-glycerin • Purification energy not included	• Substitution method, net zero
GHGenius	• Soybeans • Canola • Tallow • Yellow grease • Fish oil			

Common Assumptions:

- Transesterification with methanol (0.1 kg/kg biodiesel), natural gas process heat
- Analysis of chemical inputs other than methanol is limited (most detail in JEC and BioGrace)

Fuel Life Cycle Issues:

- Various co-product allocation methods used. Mass based credit under LCFS is larger than energy credit under EU Directive.
- Fate of fossil carbon in fuel from methanol
- Production of crude glycerin is often reported as a co-product with greater than 0.1 g/g biodiesel, while credit is applied for chemical glycerin
- Several older studies double count processing heat esterification based on misinterpretation of a biodiesel study
- Conflict between energy allocation method for energy inputs for transesterification and "substitution method" to treat carbon in fuel as zero because bio glycerin displaces fossil glycerin.
- Field nitrous oxide associated with legume nitrogen fixation uncertain
- Transesterification chemical inputs excluded from analyses

The disaggregated greenhouse gas results for plant oil biodiesel from all studies and models considered (including CA-GREET and JEC) are shown in Figure 2.11. The CA-GREET shows lower energy consumption and GHG emissions for U.S. soy biodiesel than does the JEC study for Brazilian soy biodiesel. JEC assumes much higher GHG emissions associated with farming and agricultural chemicals for Brazilian soy than does CA-GREET for U.S. soy. The lower CA-GREET result for biodiesel is also partly explained by the lower transportation distances used in the CA-GREET model. Sunflower, rapeseed, and palm oil biodiesels have lower GHG emissions in the JEC model than Brazilian soy biodiesel, sunflower oil having the lowest emissions.

All of the studies considered and shown in the figure used the displacement method to account for co-products except for the CA-GREET, which allocates inputs for farming and transesterification separately. This method first allocates energy and emissions from the farming through the oil production steps between biodiesel process feedstock oil and the animal feed co-product (e.g., soy meal residue) based on the mass share of these two product streams (mass allocation method). This method usually assigns a large credit for the animal feed meal produced, because this product is produced in greater quantity on a mass basis for many feedstocks (e.g., 80/20 split for soybean meal to soy oil). The results for feedstock oil production (including allocation for meal) and the transesterification are then allocated between biodiesel fuel and the glycerin co-product, which is based on the energy content of each product stream (energy allocation method). This approach values the glycerin as a boiler fuel. In some applications the glycerin is burned for energy; however in other applications the glycerin is refined and used as a feedstock for pharmaceutical applications. The animal feed co-product is therefore responsible for most of the co-product credit in these analyses. The allocation method is a significant issue and is discussed further in Section 4.6.

As shown in Figure 2.11, GHGenius yields lower fuel cycle emission results due to a substitution credit for both soybean meal and glycerin. The figure shows that the JEC study results for EU domestic biodiesel production are lower than for Brazilian biodiesel, largely due to feedstock and fuel transportation. Although the fuel cycle emissions are relatively low for soybean biodiesel, the LUC adders estimated for these pathways are significant, especially with the ARB LCFS and LEM analysis. The transport results vary across pathway scenarios, but net transport emissions tend to be small (except for the JEC soybean pathway evaluation with soybean transport from Brazil to the EU by ocean tanker).

The calculation of N_2O emissions differs significantly among the models. GREET calculates N_2O as a fraction of applied nitrogen. The LEM model predicts the highest level of N_2O formation.

Another variability in the pathway is associated with the energy required for soy oil extraction. These data are not widely available and many fuel LCA studies cite a biodiesel study performed by NREL (Sheehan 1998, Table 78). Early versions of GREET counted both the steam energy and the natural gas used for processing energy.

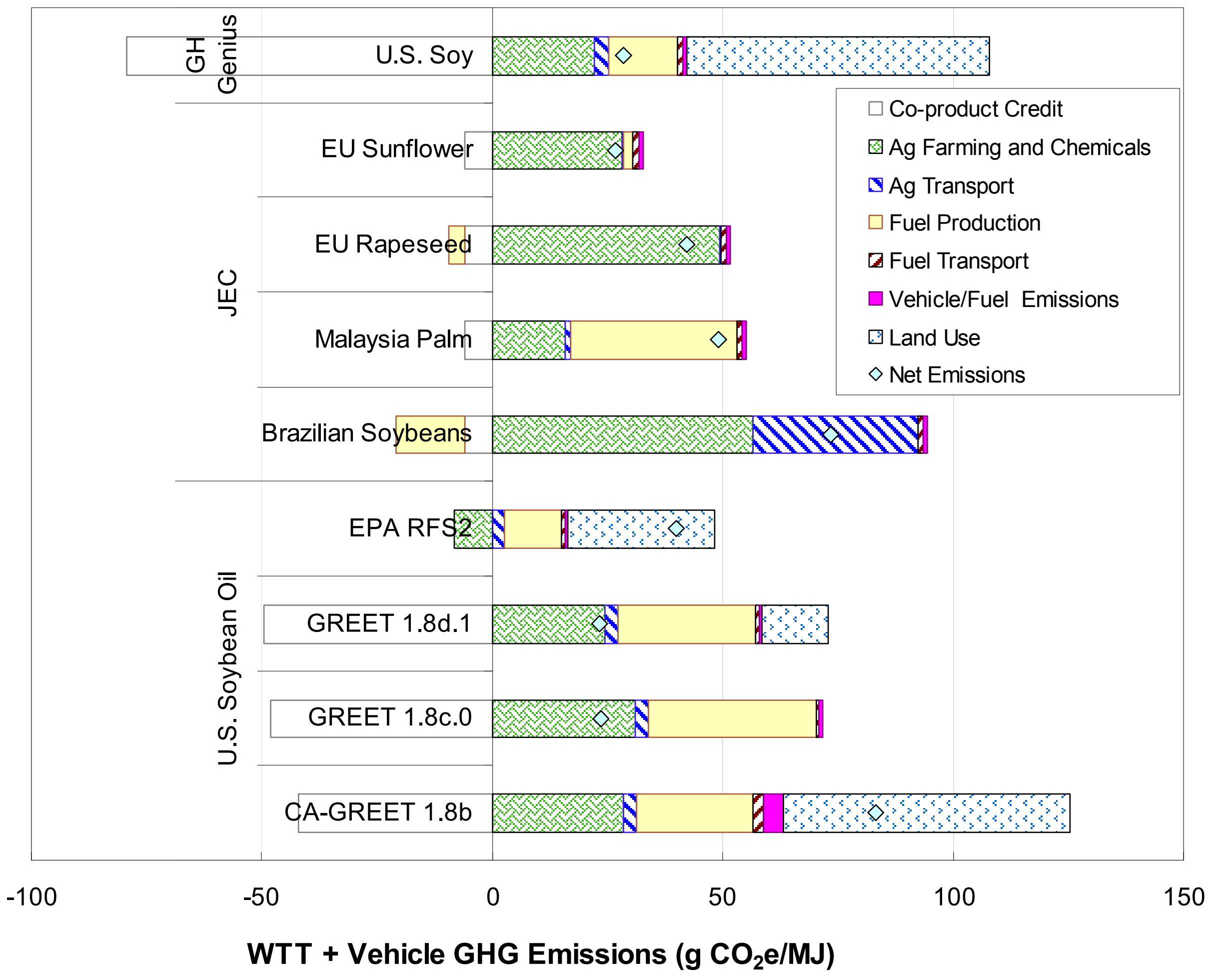


Figure 2.11. GHG Emissions from Plant Oil-Derived Biodiesel

2.3.5.5. Renewable Diesel

Renewable diesel production involves hydrotreating feedstock oil to produce straight chain paraffin (normal alkane) diesel product. GREET characterizes renewable diesels as RD I or RD II, and renewable diesels are often referred to as non-ester renewable diesel (NERD). RD I is produced by co-processing plant oils in a refinery. The RD I hydrotreating process produces straight chain paraffins, which are then converted to several refined products, including diesel. RD II is produced by hydrotreating feedstock oil in a stand-alone process. UOP and Neste Oil NexBTL® have developed RD II production processes. Table 2.20 summarizes the inputs for the soybean oil to hydrotreated renewable diesel fuel pathway, with key parameters noted in **bold** type.

Table 2.20. Soybean Oil Renewable Diesel Input Parameters

Farming					
Farming Energy	**Diesel**	**Gasoline**	**NG**	**LPG**	Electricity
Fertilizers	**N, N Share**	**N_2O Rate**	P	K	Lime
Pesticides	Herbicides	Insecticides			
Oil Seed Transport					
Heavy-Duty Truck	Distance	Capacity	Fuel Econ.		
Oil Extraction					
Extraction Energy	**NG**	Biomass	Electricity		
Solvent Use	Hexane				
Mill Performance	**Oil Yield**				
Co-Product	**Yield**	**Method**			
Oil Transport					
Heavy-Duty Truck	Distance	Capacity	Fuel Economy		
Hydrotreating					
Production Inputs	**NG**	Electricity	Hydrogen		
Plant Performance	**RD Yield**	Co-product yields			
BD T&D					
Heavy-Duty Truck	Distance	Capacity	Fuel Economy		
Ocean Tanker	Distance	Capacity	Fuel Economy		
Barge	Distance	Capacity	Fuel Economy		
Rail	Distance	Capacity	Energy Intensity		
Vehicle Emissions					
Vehicle CH_4, N_2O	EFs	Fuel Economy			

Table 2.21 summarizes the renewable diesel modeling approaches employed in the studies reviewed; study results are presented in Figure 2.12. The oil seed farming emissions dominate the fuel cycle results in all cases.

Renewable diesel (RD) emissions are difficult to compare among models/studies because of the different processes employed and the different methods of assigning emissions to feed and hydrocarbon co-products.

Table 2.21. Plant Oil Renewable Diesel Fuel Pathway Details

Model/Study	Feedstock	Technology	Co-products
GREET 1.8c.0 CA-GREET	• Soybeans grown and oil extracted in Midwest • Oil transported by rail to CA for hydrotreating	• UOP standalone hydrogenation process for RD II (same configuration as Neste Oil NexBTL®)	• Soybean meal is treated with mass-based allocation to allocate feedstock results between oil and meal • LPG is credited using the energy allocation method
JEC	• Rapeseed oil • Sunflower oil • Palm oil	• Neste Oil NexBTL® and the UOP standalone hydrogenation process for RD II • GHG emissions from farming and chemicals are very significant at 48.70 g CO_2e/MJ-fuel.	• Rapeseed meal displaces soybean meal as animal feed • 1 kg rapeseed cake by-product replaces 0.8 kg soybean meal • LPG is used internally as process fuel
GHGenius	• U.S. canola • Animal tallow	• SuperCetane, developed by CIMa energy technology centre (CETC) • Produces diesel in mixed hydrocarbon stream	• Fuel gas and heavy oil treated with energy allocation

Fuel Life Cycle Issues:

- Results vary significantly based on the co-product method used. JEC assumes LPG is burned as process fuel while GREET treats LPG as a co-product with slightly lower overall GHG impact.
- Field N_2O associated with legume nitrogen fixation uncertain.
- Palm oil emissions vary considerably with methane capture from mill effluent, co-products, and co-generation of electric power.
- Hydrogen feedstock and production method.
- The co-products produced are fuels that can be justifiably treated with energy allocation or displacement of similar petroleum fuels, with different results.

[a] CIM = Canadian Institute of Mining, Metallurgy and Petroleum

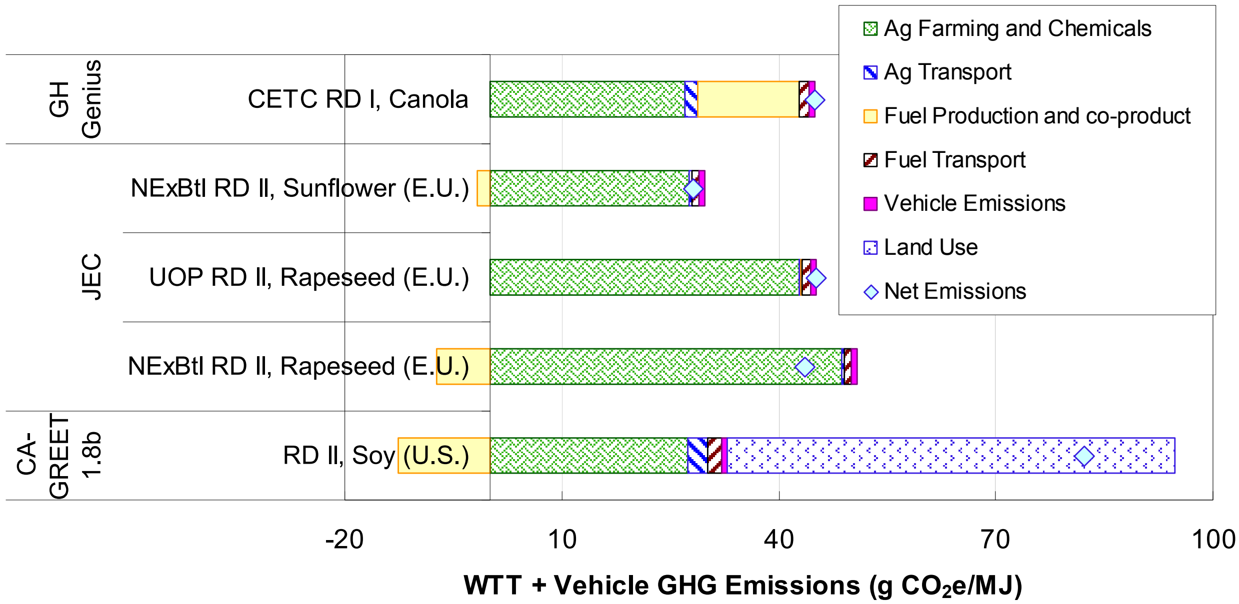


Figure 2.12. GHG Emissions for Plant Oil-Derived Renewable Diesel[20]

2.3.5.6. *Waste Materials*

Many waste materials are potential feedstocks for biofuel or power production. For example, the use of tallow and waste oil as feedstocks for FAME and hydrotreated vegetable oil (HVO) production has been examined as a pathway for the LCFS. CA-GREET treats these feedstocks as carbon neutral with no indirect emission impacts. This treatment effectively assumes that the materials would be disposed of if not used for energy recovery applications.

Municipal solid waste is also a potential feedstock for ethanol and synthetic fuel production. The treatment of the alternative fate of waste materials requires further analysis, and their treatment in the other LCA models reviewed deserves evaluation. For example, biomass materials could alternatively be used as process heat or for power generation. However, emission constraints may limit their use as feedstocks in these applications. The assumptions about the alternative fate of the waste feedstock will dominate the fuel LCA results for these materials.

2.3.6. Vehicle Operation

All of the fuel cycle studies compare fuel cycle emissions on a WTW basis, which may take into account vehicle fuel economy. Presenting WTW results on g CO_2e/mi basis allows for the comparison of vehicle/fuel technology combinations. However, WTT and TTW results are often of more interest on a fuel energy basis (g CO_2e/MJ) to separate the effect of vehicle and fuel technology. A scaling factor based on fuel economy facilitates comparison among different fuel/vehicle technology combinations. Because a broad set of vehicle/fuel/technology combinations are not manufactured and tested, a consistent set of fuel economy test data is not

[20] Results for GHGenius and CA-GREET include LUC.

available. Therefore, fuel economy is estimated from energy economy ratios (EERs), which are based both on modeling projections and fuel economy data (Figure 2.13).

The EER reflects the relative efficiency of drive train and fuel combinations with other vehicle attributes such as weight and aerodynamics held constant. EER values are determined for various vehicle and fuel combinations and are used to determine the fuel economy for a consistent vehicle or mix of vehicles. The EER is the ratio of baseline gasoline vehicle energy consumption to the alternative vehicle energy consumption (on a lower heating value basis). This value is verified with data from various studies and vehicle tests. The EER is used to adjust fuel cycle results in g CO_2e/MJ for comparison. The energy consumption is comparable for spark-ignited engines operating on different fuels with model predictions of small improvements for dedicated ethanol vehicles because of the combustion properties of the fuel[21].

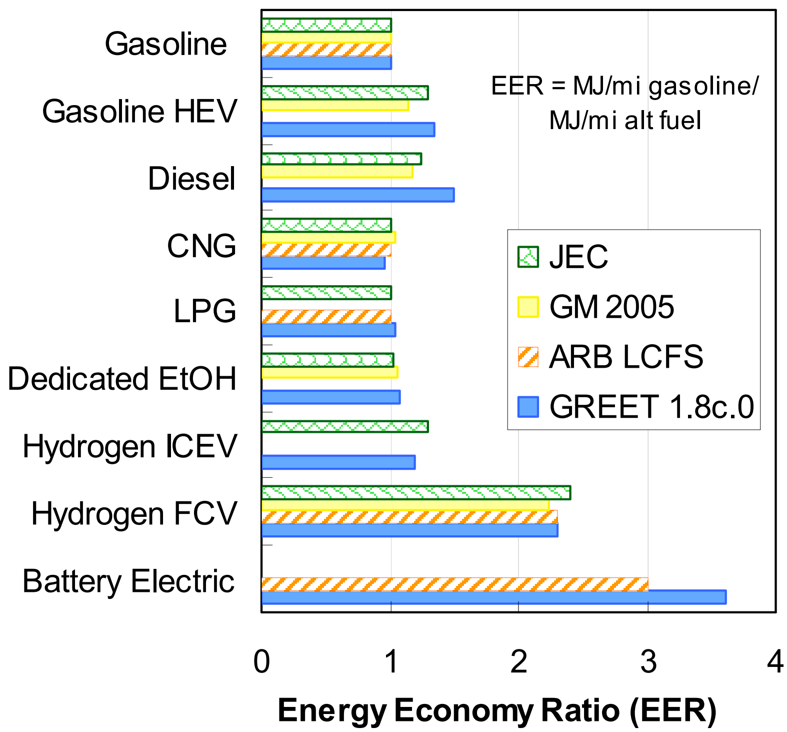


Figure 2.13. Light-Duty Vehicle EERs.

EER estimates become more variable for hybrid and electric drive technologies. The configuration of the vehicle, battery storage capacity, and other parameters affect fuel economy. Table 2.22 compares values from multiple studies. These values are exogenous to all of the LCA models and they vary depending on the vehicle modeled and vehicle weight, performance assumptions, and engine efficiency maps.

[21] The GREET model selects the EER for ethanol vehicles based on the blend level when calculating WTW results.

Table 2.22. Summary of Light-Duty Vehicle EERs

Fuel	Technology[a]	CA-GREET	GREET 1.8c	GM 2005			JEC 2008
				Baseline	Low	High	
Gasoline	ICEV	1.0	1.0	1.0	0.95	1.05	1.0
Gasoline	HEV	—	1.4	1.24	1.15	1.56	1.30
Diesel	DI ICEV	—	1.2	1.21	1.18	1.27	1.25
CNG	ICEV	1.0	0.95	0.99	0.93	1.04	1.0
LPG	ICEV	1.0	1.05	—	—	—	1.0
E85	FFV	1.0	1.05	1.0	0.95	1.05	1.03
Ethanol	dedicated ICEV	—	1.07	—	—	—	—
Hydrogen	ICEV	—	1.2	1.2	1.14	1.26	1.30
Hydrogen	FCV	2.3	2.3	2.36	2.24	2.56	2.40
Electricity	PHEV	3.0	3.0	2.46	2.63	2.81	—
Electricity	BEV	3.0	3.62	—	—	—	—

[a] ICEV: Internal Combustion Engine Vehicle; HEV: Hybrid Electric Vehicle; PHEV: Plug In Hybrid Electric Vehicle; DI ICEV: Direct Injection Internal Combustion Engine Vehicle; FFV: Flexible Fuel Vehicle; FCV: Fuel Cell Vehicle; BEV: Battery Electric Vehicle

2.4. Fuel LCA Model Observations

A review of fuel LCA models highlights many of the similarities and differences among these calculation tools. Fuel LCA models were designed with similar objectives: a WTW analysis of the GHG emissions from the production and use of conventional and alternative fuels. The regional emphasis, input assumptions, and approach to fuel LCA by the various models can lead to significantly different results.

Resolving the differences among fuel LCA analyses is desirable for many reasons. Users of the models are challenged to understand the differences among them, and a choice of model is often based on its regional adoption. Thus, stakeholders may be required to understand four or five different fuel LCA modeling platforms. Recommendations to better harmonize full fuel cycle analysis and models are presented in Section 6. The differences in fuel LCA models reflect both the approach to the analysis, regional and resource variations in data, and differences in user input, which are subject to variability. Some of the key differences among models include the treatment of marginal emissions and co-product allocation methods: Differences in results affect the ability of policies based on fuel LCA to provide credibility among stakeholders and consistent treatment globally.

What causes the differences among fuel LCA models?

- Scenarios are different with mix of process plant fuels (e.g., coal vs. gas) and conversion yields
- Different methods for handling co-products including oil refinery outputs, animal feed, glycerin, and electric power
- Different approaches to agricultural N_2O
- Real differences in regional resources
- Errors

Fuel Production Scenario

The mix of production technologies and fuel resources is significant because process heat represents about 0.4 MJ per MJ of corn ethanol product. The amount of energy required and process fuel inputs vary with plant type. The approach taken by the models also varies. Default values for GREET1.8c focuses on the U.S. average mix while BESS examines new natural gas dry mills. Several sub-pathways for biofuels are examined under the CA LCFS. Energy inputs and emissions are generally the lowest for the RFS2 analysis because the EPA uses projections for a mix of technologies for 2022.

Marginal and Regional Resource Inputs

Some fuel studies project the incremental effect of biofuel production with various levels of detail. JEC estimates the fertilizer inputs for growing marginal crops and uses estimates for fossil fuel resource. Electricity and oil production inputs for CA-GREET vary by region with marginal scenarios. The EPA estimates marginal fertilizer and farming inputs based on FASOM and FAPRI (Section 5). However, the electricity mix appears to reflect the U.S. average.

Other models use primarily average inputs. Most notably, the default GREET model is populated with parameters that reflect average inputs for power generation and petroleum production.

Transport Logistics

The effect of transport logistics varies depending on the fuel pathway. Biofuel generally requires additional truck transport to deliver fuel to distribution terminals (until pipeline infrastructure is in place). The CA-GREET model calculates these transportation impacts, while the default GREET model is based on infrastructure that is similar to petroleum. JEC also calculates transport logistics in detail, including the effects of soybean transport from Brazil and natural gas transport from Siberia. The effect of tanker ship logistics also varies among fuels. Cargo capacity and ballasting hauls can result in a 4g CO_2e/MJ difference in GHG emissions.

Errors

Many calculation and data input errors occur in fuel LCA models and are eventually corrected. Most errors results in a 0.5 to 2 g CO_2e/MJ impact, which is a relatively small fraction of the total CI but still significant. Since errors in fuel LCA models are often corrected, common types are identified below without attribution to the model.

- Upstream fuel cycle emissions not included
- Dead links, cell inputs that do not lead to calculated values; often with non-default inputs
- Incorrect fuel property of combination of carbon content and density
- Fixed values embedded in cell inputs that do not change with scenario parameters
- Pointing errors, typically when groups of cells are copied for new pathways
- Unit conversion and averaging mistakes when inputs data are translated to model parameters (for example Btu/year and gallons per year converted to Btu/gallon)
- Same energy efficiency assumed for electric and IC engine powered motors

3. Fuel Life Cycle Model Key Attributes

While fuel LCA models generally perform similarly, the usability and scope of their calculations differ. Usability attributes include format, documentation, inputs/outputs, ease of use, and flexibility, and relates to the ease of tracing input parameters through the model calculations to the final results. This section identifies respective model strengths and weaknesses, categorizes their usability, and compares their underlying calculation approach. The benefits and challenges of alternative approaches to solving these structural problems are also examined.

Documentation refers to directions for using the model (user manual), descriptions of data supporting input parameters, and procedures for formatting reports for specific fuel pathways represented in the model. Model ease of use refers to the user experience in operating the model; an easy-to-use model should facilitate quick analysis of several fuel pathway scenarios, and model controls should be straightforward and intuitive. A user interface (such as a graphical user interface, or GUI) can improve model usability, particularly for users inexperienced with the actual model, but is not necessarily an improvement over a well-organized and documented model without an interface. Scenario flexibility refers to the diversity of fuel pathways represented in a model; fuel pathways are complex, and a modular model design with numerous possible technology configurations is desirable.

The requirements for fuel LCA models are similar to those for other software products. The number of users and intended application dictate what features are necessary to make a tool usable. For example, an undocumented computer program may serve the needs of a single user. As more individuals use a software tool, their range of experience, capabilities, and research interests require a more user-friendly, versatile product. Table 3.1 indicates usability attributes and how they might vary among different applications of fuel LCA models. The attributes listed in Table 3.1 are broad categories to illustrate how models need not have all possible features to achieve their goals.

Some attributes of models are often identified as key features when in fact they simply represent a greater use of exogenous inputs. For example, the LEM calculates the GHG impact of non-traditional gases such as sulfur dioxide (SO_2) using carbon dioxide equivalency factors (CEFs). These calculations could also be performed using the criteria pollutant results from GREET in conjunction with appropriate GWP values.

Table 3.1. Usability Attributes of Fuel LCA Models

	Application of Fuel LCA			
Requirement	**Research Tool**	**Education**	**Policy Demonstration**	**Regulatory Support**
Documentation	✓	✓	✓	✓
Easy to Use		✓	✓	
User Interface		✓	✓	
Scenario Flexibility	✓	✓		

Some model features imply more accuracy than is supported by the available input data. For example, GREET calculates urban emissions that the model determines using urban share input values that are internally inconsistent for different types of equipment, and require considerable effort to use in a consistent manner.

3.1. Model Format and Documentation

Good documentation and transparent calculations are key attributes in a LCA model. Given the number of parameters and assumptions that are included in a life cycle model, it is crucial that the user understand how the calculations are performed, what assumptions were used, and how sensitive the results are to given parameters. The model itself, if transparent, can be the best source of documentation, especially if the user can discern sets of fuel pathway inputs and the calculations embedded in the model.

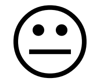
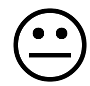
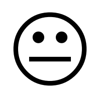
Table 3.2 summarizes the level of documentation, model transparency, and overall qualitative rating for each of the models reviewed. As the table indicates, GREET is a structured and moderately transparent model with dated but useful documentation spread throughout several documents. However, the task of tracing input parameters from the input sheet, through the calculations, to the WTT or WTW results, is very difficult and requires technical familiarity with the model.

The inputs and calculations for CA-GREET analyses are documented via detailed pathway documents. The pathway documents describe all of the calculations for energy inputs and GHG emissions for several levels of detail. A discussion of inputs that are unique to California is also provided. Many of the data inputs refer to the GREET documentation, simply the GREET model, or other fuel LCA studies and fill only some of the gaps in documentation. Model transparency and ease of use are similar to those of the default GREET model.

The documentation for GHGenius is very useful with intermittent updates. Natural Resources Canada has contracted the development of many useful documents from $(S\&T)^2$ Consultants, Inc., available on the GHGenius website. They include a model user manual ($(S\&T)^2$ 2005) and a report documenting model input parameters, data references, and detailed results for all feedstocks and fuels modeled in GHGenius (in 2006, $(S\&T)^2$ 2006). The user manual contains an overview of the model and its scope, with each section devoted to one worksheet in the model.

The reporting tool is useful for quick reference on the fuel pathways, model assumptions, and fuel pathway diagrams. The website includes a two-page input checklist summarizing the categories of input parameters in the model and their physical location in the spreadsheet. The website also provides numerous fuel pathway reports. Overall, the supporting documentation and transparency is deemed “good” despite the impenetrable model.

Table 3.2. Key Features and Documentation by Model and Rating

Model	Documentation	Comment	Rating
GREET	• Series of reports and papers on GREET website • No final report or manual for latest GREET version; rather, various update reports	• Documentation is distributed among many publications with limited description in many areas • Calculations are long and complex but can be traced with effort	
CA-GREET	• Spreadsheet with all embedded calculations • Pathway reports • Some documentation as comments in spreadsheet	• Calculations and assumptions are very hard to follow in spreadsheet • Pathway reports provide high level information; limited discussion of data inputs	
GHGenius	• Spreadsheet with all embedded calculations • Series of pathway and update reports on GHGenius website	• Reports have very good and well-organized documentation on major assumptions and results • Calculations and assumptions nearly impossible to follow in spreadsheet • No central report makes finding specific information difficult	
JEC	• Final, comprehensive reports (WTT, TTW, WTW) • WTT database is not publicly available; calculation details (such as equations used) are not available • On-line spreadsheets with supporting data and references	• Reports have very good and well-organized documentation on major assumptions and results • Detailed calculations not published in reports • Because model is not publicly available, user cannot run model to test scenarios	
LEM	• No final report, only 2003 report and 2006 draft report • Update papers and reports	• Draft report has good documentation on methodology, assumptions, and emission factors • Results are only partially published	
BESS	• Downloadable model with embedded calculations • Model generates worksheet of inputs and outputs • Final report/User's Guide	• Calculations not available to the user; embedded in model • Spreadsheet input and output files are very useful and well organized • Final report up to date	

 = Good  = Acceptable  = Poor

The JEC documentation is excellent and is updated regularly (JEC 2008). Inputs are clearly presented and results are disaggregated. Although the actual calculations cannot be directly inspected, the documentation achieves a "good" ranking because the assumptions are clearly presented, the results make sense, and the database on which the analyses are based is widely used.

LEM has a dated but comprehensive report from 2003 (Delucchi 2003) that describes the model methodology and calculations. The model is difficult to navigate and it is nearly impossible to trace calculations because macros are used to generate results instead of spreadsheet calculations[22].

BESS has less documentation than the other models, but the documentation is useful, the interface is transparent, and the inputs worksheet and output sheets generated by the model are very useful. Documentation includes a user guide with appendix (Cassman 2008), supporting material from the principal author (Liska and Perrin 2009), and several slideshow presentations. Overall, the BESS model documentation and model transparency are considered "good" despite the omissions of upstream energy and emission burdens for process fuels in the version examined.

The following subsections discuss in more detail the format, content, and documentation of the models reviewed.

3.1.1. GREET

GREET is a publicly available spreadsheet model developed at the Argonne National Laboratory (ANL) that can be downloaded and run from a user's computer. The model is a spreadsheet workbook with several macros that can be used directly or manipulated with a GUI packaged with the model download. The GUI is considered unhelpful by everyone the study team interviewed because it obscures access to the inputs and facilitates input to only a limited set of key assumptions.

GREET models emissions of the three traditional greenhouse gases (CO_2, CH_4 and N_2O) and the criteria pollutants. Global warming potential values are used to aggregate the three GHG species emissions into a single carbon dioxide equivalent result. Volatile organic compounds (VOC) and carbon monoxide (CO) are counted in their fully oxidized forms as carbon dioxide[23].

The main sheets in the GREET workbook include a summary of the main input parameters for all fuel pathways, a fuel production time series sheet, which contains input parameters varying by target year, fuel pathway sheets that calculate results, and a results sheet summarizing the WTW results in g/mi for most fuel pathways. Inputs to the model are executed in several input sheets. In addition, data are inputted on a time series sheet, on worksheets for each fuel pathway, and inside calculation cells. The variety of input locations is confusing to users without extensive GREET experience.

The "Vehicle" sheet organizes vehicle fuel efficiency and emission factors. The model does not show the fuel carbon separately from combustion methane and nitrous oxide for tailpipe emissions. Most analysts want to understand the fuel carbon separately from the combustion

[22] LEM and GHGenius share a similar model structure.

[23] GREET first calculates CO_2 emissions by subtracting the carbon in VOC, CO, and CH_4 from the carbon that is combusted to form CO_2. The fully oxidized VOC and CO are converted to CO2 via their molecular weight. For example CO emissions × 44/28 = CO_2. The GREET approach does not count the oxidized CH4 emissions. This minor omission conflicts with the IPCC's guidance on global warming potentials (IPCC 2001) See Section 4.2.5.

methane and nitrous oxide and compare WTW emissions on a g CO_2e/MJ basis. The model does not present results by fuel pathway component or even present WTT and TTW emissions in g/MJ in one convenient place. The model does present WTT results disaggregated into "feedstock" and "fuel" results, but further disaggregation requires considerable effort.

The GREET model includes provision for a wide range of feedstocks, fuels, and vehicles. GREET models more than 100 fuel production pathways and more than 70 vehicle/fuel combinations for the time period 1990 – 2020 in five-year increments. GREET models light- and heavy-duty conventional spark ignition vehicles, direct injection spark and compression ignition vehicles, grid-independent hybrid electric vehicles, grid-connected hybrid vehicles (PHEVs), battery-powered electric vehicles (BEVs), and fuel cell vehicles (FCVs). GREET2.7 is a vehicle cycle model that calculates the energy and emissions associated with the vehicle life cycle, from raw material production (the life cycle emissions of materials used in the vehicle) through vehicle recycling. This model calculates vehicle production results for the vehicles represented in the GREET fuel cycle model.

The documentation for GREET is extensive and is accessible through the ANL website. Nonetheless, there is not one all-encompassing, up-to-date report on the most recent version of GREET. GREET documentation spans over 10 years, with initial reports and subsequent update reports and user manuals. Therefore, finding the answer to a specific question about an assumption or calculation in the model is not straightforward. Documentation to GREET1.8d.1 is provided through a brief memo that describes the references for 11 updates to the model. Many of these changes refer to peer-reviewed journal articles. While the use of publications to support model inputs is commendable, journal articles do not fill the need for a comprehensive set of documentation. The result of the current approach is a patchwork of inputs and analysis that is not comprehensive.

Several updates of GREET have been released in recent years. Version 1.8c is used by the EPA for the RFS2 analysis. Version 1.8b was modified for the LCFS with many of the changes implemented in version 1.8c. Version 1.8d.1 is the most recent version.

3.1.1.1. GREET for RFS2

The default GREET has also been modified by the EPA to model fuels under the RFS2 (GREET 1.8c). The EPA created four model files based on this version to model electricity, ethanol transport, fertilizer production, and sugarcane transport. The model inputs primarily reflect differences in resource mix.

3.1.1.2. CA-GREET

The default (unmodified) GREET model has been revised and modified (by Life Cycle Associates for ARB, ARB 2009c) to become CA-GREET to model fuels used in California under the LCFS. The CA-GREET model was developed starting with the previous version of GREET (1.8b, 09/2008 release). The CA-GREET model differs from the default version in three main ways:

1) CA-GREET has a regional lookup table with regional inputs that allows a user to select from eight regions in a pull-down menu, representing feedstock and fuel regions involved in the production of California fuels and California-specific input parameters rather than U.S. average parameters.
2) Calculation errors in GREET1.8b have been corrected (GREET1.8c.0 corrects most calculation errors as well).
3) Calculation components have been added; new fuel pathways have also been added using the existing GREET structure. The model is configured for CNG and LNG from dairy digester gas and landfill gas, respectively. The model is also configured for waste cooking oil and tallow pathways. The model is not populated with all of the inputs for numerous sub-pathways such as corn and sugar cane ethanol. Most sub-pathway inputs require user modifications to the inputs.

CA-GREET calculations are contained in a spreadsheet, which is publicly available and not user-protected. The user can download the spreadsheet, modify any of the inputs or formulae, and observe the effects on the results and intermediate calculations. However, the CA-GREET fuel sheets are not easy to follow, equations embedded in each cell can be very long (3-4 lines), and the dependent cells are often located in different worksheets. The spreadsheet does not show many intermediate calculations or results. This said, all the calculations are contained in the CA-GREET spreadsheet, and can be followed and understood, albeit with considerable effort.

The inventory data contained in the GREET model is derived from the DOE Energy Information Administration (EIA) and the EPA, with simulated fuel economy results from Argonne's Powertrain System Analysis Toolkit (PSAT) model. There is no text documentation for the EPA GREET file, but the spreadsheet files are available in the RFS2 docket online. ARB has released fuel pathway reports for the LCFS that document fuel pathway inputs, calculations, and results from the CA-GREET model in some detail, and are available on the ARB website. However, the fuel pathways documents (one per pathway) often show only general results and do not explain or document input parameters. If a user needs to understand the calculations underlying a result, he/she must refer to the individual pathway CA-GREET spreadsheet. An instructions sheet near the front of the model provides directions for calculating results for each fuel type. No published user-manual is available.

3.1.1.3. GREET 1.8d.1

The most recent version of the GREET model is version 1.8d.1. The model contains updates to petroleum refinery efficiency and several fuel pathways. The most significant modifications are a more detailed assessment of the displacement of DGS based on its uses as feed (Salil 2008). The model estimates the amount of corn and soybean meal displaced, depending on the feed requirements for poultry, swine, and cattle. The model also includes an additional spreadsheet that calculates the LUC impacts associated with corn ethanol (Section 5).

3.1.2. GHGenius

GHGenius is a spreadsheet-based model, based on a 1998 version of the LEM, parameterized for Canada and expanded to model additional fuel pathways and scenarios by $(S\&T)^2$ Consultants for Natural Resources Canada, as noted above. Like the LEM, GHGenius can calculate energy and emissions associated with conventional or alternative fuel production for the past, present, and future (through 2050). GHGenius includes the three traditional greenhouse gas emission constituents in addition to CFC-12 and HFC-134a; the model also includes the criteria pollutants. GHGenius uses GWP values rather than CEFs to aggregate greenhouse gas emissions to a total g CO_2e value, although the model allows the input of CEFs or other metrics for aggregating emissions.

The model workbook is organized with dozens of worksheets, similar to GREET, but the model is much more difficult to decipher than GREET. Some of the worksheets are labeled, but many are designated with only a letter, making it difficult to navigate the model and understand the linkages between worksheets. The lettered worksheets are not organized alphabetically or by any other obvious characteristic. This means that tracing the input parameters through the calculations to the finished results is quite difficult. However, the model does present WTT results by fuel pathway component (disaggregated results), a feature lacking in GREET. Unfortunately, after navigating to a given worksheet described in the user-manual, the calculations included in the model are difficult to decipher. Moreover, fuel pathway calculations are spread across multiple worksheets (instead of organized in one sheet per fuel, like GREET) and much is accomplished using embedded macros.

The GHGenius model includes many more alternative fuel pathways than LEM, but only models the fuels for light-duty vehicles, class 3 to 8 heavy-duty trucks, urban buses, light-duty BEVs, and FCVs. There are currently more than 200 vehicle, fuel, and feedstock combinations (pathways) represented in the model. LEM models a wider range of vehicles, including mini-buses, mini-cars, mini-scooters, and the like, but contains fewer alternative fuel pathways. GHGenius calculates results for several different regions of interest, including three sub-regions of Canada (east, central, and west), the United States, Mexico, and India.

Most of the U.S. data are identical to the data in LEM and are derived from the EIA databases. These databases include historical data and future projections for electric power, crude oil, refined petroleum, natural gas, and coal production. Other U.S. inventory data are sourced from the U.S. Census Bureau. The non-energy related process emissions in the model are based mostly on the EPA AP-42 emission factors. For Canada, the data are derived from Statistics Canada, Natural Resources Canada, Environment Canada, the National Energy Board, the Canadian Association of Petroleum Producers, and the Canadian Gas Association. The emissions from vehicles for conventional fuels in Canada are derived from the Environment Canada model Mobile 6.2C. For Mexico and India, the model adheres to a hierarchical method of obtaining inventory data, in which data are prioritized in the following order: industry average values, then actual operating plant operating data, then engineering design data, and finally estimated data from pilot plants, engineering simulations, or scientific experiments. Documentation for GHGenius includes a documentation manual from 2003, a user manual from 2005 for model version 3.0, and an introduction to the GHGenius report prepared in 2006, all available on the GHGenius website.

3.1.3. JRC/EUCAR/CONCAWE (JEC)

JRC, EUCAR, and CONCAWE (JEC) have conducted a joint evaluation of WTW energy and greenhouse gas emissions associated with a wide array of conventional and alternative fuels and vehicle powertrain options. The analysis is based on software developed by Ludwig-Bölkow-Systemtechnik GmbH (LBST). The software combines a database for all input data and references, with an algorithm for the calculation of the total energy and GHG emissions associated with a given pathway, including feedback loops. The most recent results released are available at the JRC website. The model software is not publicly available (although the LBST database can be purchased); thus the user cannot make changes to the inputs, assumptions, or calculation approach. The analysis considers 2002 and future (2010+) technologies.

The JEC analysis models 14 fuels, and includes several feedstocks for many of the fuels, resulting in a total of over 100 fuel pathways. All fuel pathways focus on fuel used in the EU; most of the feedstocks and all of the fuels are produced in the EU. The pathways for soy oil biodiesel and sugarcane ethanol are based on Brazilian feedstock production. The analysis considers only one vehicle type, represented as a theoretical five-seat European sedan (similar to a Volkswagen Golf). NREL's **AD**vanced **V**eh**I**cle **S**imulat**OR** (ADVISOR) model was used to simulate this European sedan for the TTW component of the analysis. The reference vehicle has a 2002 port-injected, spark ignition, gasoline powertrain.

JEC's reports and appendices with results tables provide a good explanation on the methodology of the calculations. However, the documentation does not show the equations used or many of the parameters and assumptions employed in the equations. For example, N_2O emissions from biofuel crop production are shown on a per-crop basis, but the equations used to calculate those emissions are not shown. The results presented include "sub-pathways" with differing assumptions on energy use, co-product fate, and other assumptions for each fuel/feedstock pathway. The JEC documentation and results are presented separately in WTT, TTW, and WTW sections. Each has a comprehensive report and appendices with detailed results for each pathway, broken down by life cycle stage. Each report section shows disaggregated results by pathway component, including "best estimate" values, and minimum and maximum values based on Monte Carlo simulations. The minimum and maximum values are those at the 20% probability and 80% probability, respectively. The reports also present net energy expended (direct energy use) and total primary energy consumed.

3.1.3.1. BioGrace

The BioGrace model provides the default values in a spreadsheet for the EU Renewable Directive. The calculations meet the requirement of Annex V (2009/28/EC) of the Directive. The BioGrace model is available for The Netherlands with parameters that are consistent with the JEC analysis. A key feature of the analysis is energy allocation for co-products.

BioGrace provides over 15 biofuel pathways in separate workbooks. The calculation scheme for each pathway is consistently organized and easy to follow. BioGrace follows the functional unit approach laid out in the JEC report. Energy inputs and emissions are calculated per unit of throughput such as a tonne of sugarcane. The emissions are converted to a per MJ basis using a cumulative yield factor, which reflects all of the yields for each processing step.

BioGrace is configured with the energy allocation approach specified under the EU Directive. Thus, the tool is not configured to provide the flexible options for examining co-products as in other fuel LCA models.

Another significant feature of BioGrace is the exogenous LCI data. These parameters are external model inputs, whereas they are calculated internally in GREET, LEM, and GHGenius.

3.1.4. LEM

The structure and approach in the LEM are similar to those in GHGenius, because GHGenius was developed from an early version of LEM. LEM has continued to evolve, to expand the fuel pathways included in the model and update the inventory data. The model is probably the most extensive model reviewed here, tracking traditional and non-traditional greenhouse gases and criteria pollutants, and estimating indirect land use change impacts. The LEM provides a more detailed analysis in areas such as agricultural emissions of nitrogen compounds, petroleum flows, and vehicle performance. The LEM is the most complex and difficult model to understand. The model consists of several linked worksheets and several macros used to run simulations. Fortunately, all of the worksheets are labeled, but many of the worksheets are poorly organized and labeled internally, making it difficult or impossible to understand calculations or trace input values through the model. Unlike GREET, in which each fuel is organized into a separate worksheet, LEM groups all alternative fuel production in one worksheet, while modeling bio-feedstocks on separate worksheets. Many of the simulation calculations are performed by macros rather than explicit spreadsheet calculations, further hindering model transparency.

The model includes over 100 fuel pathways and numerous vehicle options from 1970 - 2050, including mini-buses, mini-cars, motor scooters, bicycles, transit systems, and commercial/ industrial vehicles. Unlike the other fuel cycle models, LEM compares and aggregates different greenhouse gas species based on CEFs rather than using the IPCC GWP values. The CEF is a damage function based on the incremental change in global temperature associated with an emission increment, whereas GWP values are based on climate forcing processes. LEM's principal author (Dr. Mark Delucchi) argues that CEFs (or true GWPs) depend on the relative concentrations of climate species in the atmosphere; therefore their values vary over time. The LEM uses time-varying CEF values to aggregate the emission results for different emission species, which complicates an analyst's efforts to determine the portion of the results that are due to varying CEFs. The CEFs for most climate species consist of several components, each representing a separate mode by which the emissions impact climate.

Documentation of calculations and assumptions is available in separate reports and appendices contained on the University of California, Davis website. A detailed report was published in 2003 (Delucchi 2003). Thus, documentation of methodology and assumptions is good, but the LEM is very lacking in results reporting. Moreover, the LEM was never completed. Therefore, results are difficult to locate and they are incompletely reported (e.g., many pathways and results tables are missing from the report or only parts of some tables are included). We could only find one table with upstream (WTT) GHG emissions per energy unit of fuel, and this table only contains a few pathways. According to the report, the LEM can generate very detailed WTT, TTW, and WTW results for a wide variety of scenarios, but these results are not reported. Hence, while the LEM contains good reference material for emission factors and biofuel LCA methodology, it is not a reliable source for results.

3.1.5. BESS

BESS is a software tool developed at the University of Nebraska Lincoln (UNL) that calculates the energy efficiency, greenhouse gas emissions, and fossil fuel requirements associated with dry mill corn ethanol production. BESS includes treatment of crop production, ethanol bio-refineries, cattle feedlots, and anaerobic digestion (optional). The latter considers digestion of cattle manure to generate biogas. Corn and ethanol transport are included in the analysis. The model includes several preconfigured sets of input parameters that represent a range of bio-refinery scenarios. The model will be expanded in the future to include corn stover and switch grass to ethanol pathways.

The tool can be downloaded for free for non-commercial users; commercial users must purchase a license. The model features a user-friendly graphical user interface (GUI) and the latest version is 2008.3.1. The model does not show the embedded calculations and the calculations cannot be altered, but BESS can print out a spreadsheet of results with inputs and emissions for each life cycle step for corn ethanol production. Therefore, while BESS is user friendly and provides a detailed accounting of fuel cycle emissions, the actual calculations cannot be readily inspected. Some transport calculations omit upstream energy and emission burdens for transport fuels. The model has a "Parameters" tab showing input parameters and emission factors. Documentation includes a user's guide, and a slide show presentation, available on the UNL BESS website.

3.2. Model Usability

In order to assess the "usability" (i.e., user-friendliness) of the analyzed models, the project team exercised the models for two fuel pathways, herbaceous biomass to cellulosic ethanol and corn ethanol.

The herbaceous biomass pathway specifications were:

- Target year 2010
- Cellulosic ethanol (herbaceous)
- Fermentation process
- Dedicated light-duty gasoline vehicle using 100% ethanol

The following outputs were analyzed:

- WTT results in *energy* per unit *energy* of fuel
- WTT results in *GHG emissions* per unit *energy* of fuel
- WTW results in *energy* per *distance* traveled.
- WTW results in *GHG emissions* per *distance* traveled
- "*Motive WTW*" results in *GHG emissions* per unit *energy* of fuel delivered to the wheel
- Breakdown of GHG emissions

Table 3.3 summarizes the team's experience simulating the herbaceous ethanol fuel pathway in the models considered. As the table indicates, the GREET GUI receives the poorest ranking because the GUI allows specification of a small subset of GREET inputs, and users must proceed through the entire program to determine the effect of changing just one parameter. This means that running simulations for multiple pathway scenarios is laborious and time-consuming.

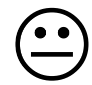
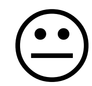
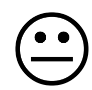
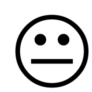
Using the GREET model or CA-GREET is a better experience than using the GREET GUI, as the user can specify any or all of the input parameters, which are relatively well-organized in two worksheets, and inspect the calculations. However, cell formulas are lengthy and difficult to understand unless one is very experienced with GREET. The procedure for updating a calculation or the entire model is not readily apparent. Using the GHGenius is slightly less straightforward than operating the GREET spreadsheet due to poor labeling on worksheet tabs. However, the input parameters are well-organized in the "Input" sheet and a user-friendly button located on the page runs the model.

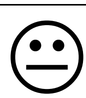
The JEC analysis is very transparent for a model that is not publicly available, and the documentation and results are user-friendly. The LEM is not publicly available. Earlier versions of the LEM examined by the project team were comparable to GHGenius in usability with differences in labeling. It is more difficult to run simulations because the model doesn't have buttons to activate the necessary macros. Moreover, the LEM has not been set up for public use. The BESS model is the only model judged "good" through one exercise (simulating corn ethanol). The model is easy to use and understand and the results are presented in a clear, useful manner by fuel component. BESS also facilitates sensitivity analysis by simulating and comparing two different corn ethanol runs simultaneously.

3.3. Model Availability

GREET is a freely downloadable model that can be accessed through the Argonne National Laboratory website. CA-GREET and GHGenius spreadsheets are publicly available, not user-protected, and easy to download. The accompanying reports can be downloaded as well. JRC and LEM reports can be found in the respective model websites and freely downloaded. JRC data spreadsheets were also available in 2010. The BESS model is freely downloadable in its non-commercial version but requires a license for commercial users.

Table 3.3. Usability Rating of Models for Test Runs of Corn Ethanol and Herbaceous Biomass Ethanol

Model	**User Ability to Change Inputs**	**Transparency of Calculations & Assumptions**	**User Ability to Perform Sensitivity Analysis**	**Rating**
GREET GUI	Limited ability to change inputs; lengthy sequence of windows before calculation	Calculations are embedded in the model and not available to user; lack of proper documentation.	User can vary one input at a time in model and analyze effects on results. However, user has limited ability to modify inputs	
GREET and CA-GREET	User can modify inputs in spreadsheet	Calculations, assumptions, and intermediate results are very hard to understand in the spreadsheet	User can perform sensitivity analysis by varying one input at a time in spreadsheet and analyzing effect on results	
GHGenius	User can modify inputs in spreadsheet	Calculations are difficult to understand and model is difficult to navigate	User can perform sensitivity analysis by varying one input at a time in spreadsheet and analyzing effect on results	
JEC	No ability to change inputs because model is not publicly available; the LBST database can be purchased, however.	Assumptions, intermediate results, and final results are clearly noted	User can relatively easily replicate equations and assess relative importance of parameters, but not perform a sensitivity analysis	
BioGrace	Summary of LCA results, not an LCA model.	Assumptions tied to JEC analysis	Users have access to spreadsheet data for number fuel pathway components. Users can easily develop new pathways.	
LEM	No ability to change inputs since model is not publicly available	Assumptions well documented and calculation formulae are listed. However, results are not noted.	The equations used in the model show impact of different factors on final results	
BESS	User can change multiple inputs and calculate results quickly	Assumptions are well documented. Intermediate and final results are clearly noted.	User can perform a comparison of two different runs and hence perform a sensitivity analysis	

 = Good  = Acceptable  = Poor

3.4. Model Outputs

GREET, CA-GREET, JEC, LEM, and GHGenius are transportation fuel carbon intensity models based on life cycle analysis. This life cycle analysis represents the GHG emissions associated with the raw material and fuel production, transportation, and, in some cases, use of the fuel in vehicles. Carbon emissions can be expressed in different terms, depending on what life cycle steps were considered in the calculation:

1. *At-the-pump/plug*: Emissions are measured per MJ entering into the vehicle, at the tank for liquid fuels and at the battery for plug-in vehicles (e.g., g CO_2e/MJ-fuel delivered to vehicle). This value does not take into account the differences in fuel economy of different vehicle types or their use. This represents the **WTT** result.
2. *Per-mile*: Emissions are measured per mile driven, e.g., g CO_2e/mi. This represents a well-to-wheel result (**WTW**). This value takes full account of vehicle fuel efficiency, including (a) engine and drive train efficiency, which represents the efficiency with which fuel is converted to motive power for a given fuel/vehicle category and (b) other vehicle efficiency considerations that require in-depth knowledge of the type of vehicle, including vehicle weight, air drag, rolling resistance, and other parameters.
3. *At-the-wheel (motive energy)*: Emissions are measured per MJ delivered to the wheel to move the vehicle, e.g., g CO_2e/MJ delivered to wheel after combustion of fuel. This may be termed a "**motive WTW**." This metric takes into account the engine and drive train efficiency of a given fuel/vehicle combination (see 2(a)), but not the other vehicle-specific considerations (see 2(b)).

Understanding the differences between these different emission reporting categories is crucial in understanding the results reported by the various LCAs. GREET, JEC, LEM, and GHGenius are well-to-wheel models. These models also include an analysis of vehicle efficiency, i.e., distance traveled per unit fuel usage. The fuel efficiency parameter makes it possible to calculate the carbon intensity of fuels on a per-distance-traveled basis, and not just on a per-fuel-energy basis, i.e., the carbon intensity results are presented both as g CO_2e/MJ-fuel and g CO_2e/mi. As mentioned above, in order to determine vehicle efficiency, these models include detailed analyses of vehicle and motor type and performance. BESS, on the other hand, is a WTT-only model. It does not take vehicle considerations into account.

The ARB's use of the CA-GREET results for the LCFS is in between those two categories and falls within the "motive WTW" study. The CI equals the WTT plus TWW values divided by a unitless drive train efficiency or energy economy ratio (EER). The EER is the ratio of the baseline vehicle's energy consumption to that of the alternative-fuel vehicle's energy consumption. The CI is the WTT carbon intensity measured in g CO_2e/MJ *plus* the emissions resulting from the *combustion* of the fuel.

Because the carbon in fuel is independent of the vehicle technology used to combust the fuel, and vehicle methane and nitrous oxide emissions are small, the LCFS analyses are largely independent of the precise vehicle type (after accounting for the EER). The reporting metric for the CA-GREET/LCFS and the EPA's RFS2 are comparable except the EPA model examines emissions over a different time horizon extending to 2022.

To summarize, the carbon intensity in CA-GREET includes:

- WTT carbon intensity
- GHG emissions resulting from the combustion of the fuel
  - CO_2 emissions from oxidized fuel carbon, determined from fuel properties
    - All carbon assumed to oxidize to CO_2 and counted
    - Carbon in biofuels considered "biogenic" and credited back
  - CH_4, N_2O calculated separately based on engine technology
- Adjustment for the drive train efficiency of the vehicle compared to a baseline gasoline or diesel engine using an EER

3.5. Fuel Pathways

Fuel pathways are feedstock/fuel combinations; for example: corn to ethanol, wheat to ethanol, or landfill gas to CNG. Within one pathway, there can be different sub-pathways with different inputs and/or assumptions. For example, for the corn ethanol fuel pathway, the bio-refinery can use a conventional natural gas boiler, gas turbines with heat recovery, coal boiler, corn stover boiler, etc. The main feedstocks can include crude oil, waste oil, natural gas, biomass, biogas, sugar crops, starch crops, oil crops, and algae. The feedstocks are converted to finished fuels via many different conversion processes; finished fuels are then used in different vehicle types. Figure 3.1 illustrates fuel pathway combinations, which include the feedstock, conversion process, finished fuel transport, and vehicle technology. Co-products are not explicitly represented in Figure 3.1, though they are an important factor in the life cycle analysis. Most co-products can be used for many purposes and there are several methods for calculating co-product emission credits in life cycle analyses. For example, glycerin from biodiesel production is refined for use in pharmaceutical products. Glycerin is also used as animal feed and boiler fuel. Similarly, distiller's grains and solubles (DGS) can be used as both animal feed and process fuel. When the co-product is used as a fuel in the biofuel process, it displaces other fuel inputs. Many of these uses of co-products are examined as flexible features in GREET.

JEC, GHGenius, and CA-GREET all have a large number of pathways that are relevant in their target regions. For example, JEC (EU focus) does not include corn ethanol, and CA-GREET (California focus) does not include wheat ethanol. JRC, CA-GREET, and GHGenius include landfill gas as feedstock for natural gas fuel production, and JEC and CA-GREET also include animal manure. For ethanol and biodiesel, GHGenius includes many pathways (feedstocks), and JEC and CA-GREET include the most common options considered in the EU and California, respectively. JEC includes both renewable diesel and synthetic diesel, whereas CA-GREET does not include synthetic diesel in its fuel mix. CA GREET will need to examine other fuels and pathways, and the ARB has established clear methods for fuel providers to submit a fuel pathway for consideration. GHGenius, JEC, and LEM have several hydrogen pathways, whereas CA-GREET examines two cases. LEM incorporates farmed wood as a feedstock for CNG, ethanol, methanol, electricity, and hydrogen. It also incorporates several pathways for electricity and hydrogen, but only includes one pathway for biodiesel (soy) and two for ethanol (corn and farmed wood).

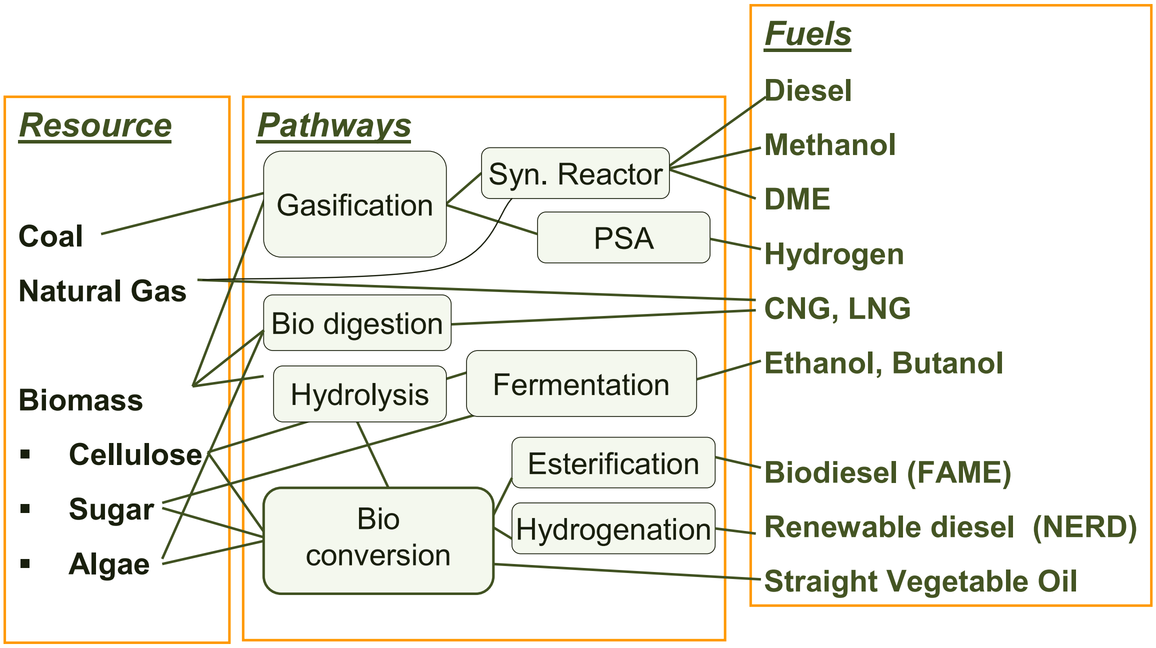


Figure 3.1. Fuel Pathway Feedstock, Conversion Technology, and Fuels Combinations

3.6. Fuel LCA Calculations

The two main types of models reviewed here are linked spreadsheet models and database-based models. The linked spreadsheet model approach calculates all results within the model structure, which means there are numerous interdependencies between fuels and circular references within individual fuel pathways. The database approach, employed by the JEC analysis, relies on a database of life cycle inventory data, rather than calculating the results within the model. Table 3.4 summarizes the main issues and factors associated with fuel cycle analysis.

3.6.1. Data Uncertainty and Sensitivity Analysis

The major areas of uncertainty in fuel life cycle assessment include:

- Emissions related to changes in cultivation and land use (direct and indirect)
- N_2O emissions from agricultural processes and inputs
- Treatment of market-mediated effects (e.g., co-products, changes in process emissions in response to changing production quantities)
- Natural gas leakage from pipelines
- Carbon equivalency factors (GWPs, CEFs) for GHGs
- Climate impacts of emissions

Table 3.4. Summary of Fuel LCA Calculation Features

Topic	Model Parameter/Attribute	Comment
Life Cycle Calculations	• Fuel cycle summation • Loss factors • Iterative calculation	• Need to both track fuel inputs and results based on fuel inputs. • Transport fuel pathways (natural gas, diesel, electric) should be decoupled from process fuel inputs
Life Cycle Inventory Data	• Endogenous calculation with simple life cycle calculation • Input from LCA database	• Varies by region • Depends on regional electricity and resource mix • LCI calculations are not well documented
Metrics	• WTW (g/mi) • WTT (g/MJ) + Vehicle Emissions • Global Inventory (tonnes) • Biogenic CO_2 • Energy metrics	• Several energy and carbon accounting schemes possible; accounting scheme should be declared • WTW (g/mi) metric obscures WTT results by placing emissions on a per mi basis
GHG Species	• IPCC GWP factors • Non CO_2 gases • Indirect GHGs	• All models include traditional, direct GHGs • Indirect effects depend on criteria pollutants, their radiative forcing, and lifetime in the atmosphere
Scenario	• Average • Marginal • New technology • Predictive	• Approaches to averaging and consequential analysis • Timeframe for scenarios
Fuel properties	• Carbon content • Blending • Connection to process modeling and fuel composition is often inconsistent	• Fuel properties have significant impact on results and are easiest parameters to correct • Opportunity for confusion between higher and lower heating value
Vehicle energy use/emissions	• Energy use (Btu/mi, MJ/mi) • Combustion CO_2 • Combustion CH_4, N_2O	• Energy use based on vehicle simulation software • CH_4, N_2O based on vehicle emission factors
Uncertainty	• Uncertainty analysis tool • Data and scenarios for uncertainty	• Uncertainty should be assessed by stochastic analysis after determining key parameters

Most models omit uncertainty and sensitivity analysis, or conduct a very limited analysis. The GUI for the default GREET model contains a stochastic simulation module that can be used for uncertainty analysis for a single target year. The distribution data contained in the "Dist Spec" sheet in GREET include the distribution shape, minimum and maximum values, and likeliest values. CA-GREET does not conduct an analysis, although various scenarios and sensitivity analyses are performed for both the WTW and LUC analyses.

The JEC analysis does include an uncertainty analysis based on Monte Carlo simulations. JEC results are presented with an associated margin of error. The analysis report documents "minimum" (20% probability), "maximum" (80% probability), and "best estimate" values for some parameters used in the calculations, as well as in the final results. GHGenius has the capability of performing a full Monte Carlo sensitivity calculation and has a built-in Monte Carlo worksheet. Therefore, GHGenius performs the most sophisticated sensitivity and uncertainty analysis of the LCA models reviewed. BESS is the only life cycle tool with a GUI capable of sensitivity analysis. BESS conducts sensitivity analyses of model input values on biofuel system performance and emissions using different combinations of cropping systems, production technologies, and co-product utilization schemes.

LEM provides a discussion of the model parameters that have the highest associated uncertainty. The LEM report makes some allusions regarding the sensitivity of model results to certain parameters. For example, the report notes that fertilizer usage and loss through evaporation, leaching, etc. on N_2O emissions and CO_2 uptake from fertilized vegetation have a large effect on results. Construction materials (for example for power plants and infrastructure) have a small effect on results. Emissions associated with land use change have a potentially very large effect. However, the LEM report does not present a separate section discussing sensitivity and the model does not have a built in method for assessing uncertainty. A cursory review of LEM indicates results are likely to be highly uncertain due to the scope and complexity of the model. LEM attempts to model multiple countries for over 50 years, tracks nitrogen and sulfur species through dozens of ecosystem types, defines the composition of the atmosphere to 2010, estimates CEF values based on these compositions, and estimates ultimate damages resulting from modeled increments in emissions. The model is overly ambitious in this regard.

3.6.2. Fuel Properties: Units and Metrics

In most cases, data on detailed feedstock properties are not necessary to conduct fuel pathway analysis. The only metric needed is the fuel yield per unit of feedstock input. For biomass-based fuel pathways, the feedstock water content (primarily applies to biomass or pyrolysis oil) is also required to accurately account for the associated water transport during feedstock transport to a processing facility. For bio-oil (e.g., algae) feedstocks converted to biodiesel or renewable diesel, fatty acid profile data are useful for estimating co-product yields. The fatty acid profiles can also be used to estimate the feedstock and fuel heating values, absent empirical heating value data for a feedstock oil or resulting fuel product.

The produced fuel properties have a big impact on fuel cycle results. Accurate fuel properties are important because fuel cycle results in g/MJ depend on the energy content (Btu/gal, MJ/tonne, Btu/ft^3) of the fuel produced. Tailpipe GHG emissions (g CO_2e/MJ fuel) depend on the fuel density (g/gal) and the mass percent carbon content of the fuel. For fossil fuels, the sulfur content of the fuel is also important, as it relates to sulfur oxides (SO_x) emissions and energy requirements to remove sulfur from the fuel product.

3.6.3. Vehicle Attributes

As mentioned in Section 3.4, some life cycle models incorporate a very detailed analysis of vehicle efficiency in order to calculate TTW emissions. These models take into account the efficiency of the vehicle in conjunction with a particular fuel. JEC, GREET, GHGenius, and

LEM are such models. On the other hand, BESS does not include any aspect of fuel product and is not concerned about vehicles. Table 3.5 below shows an example of fuel/vehicle combinations for the GHGenius model. EER estimates are exogenous to all of the fuel LCA models. The methods used to assess fuel efficiency vary as discussed in Section 4.7. Calculating vehicle/fuel combinations is simply a matter of estimating vehicle CH_4 and N_2O and calculating CO_2 in proportion to fuel consumption.

Table 3.5. Fuel/Vehicle Combinations in GHGenius

	Vehicle					
Fuel	**ICE LDV**	**ICE HDV**	**Hybrid LDV**	**Hybrid HDV**	**Fuel Cell LDV**	**Fuel Cell HDV**
Petroleum diesel	√	√	√			
Gasoline	√	√	√		√	
FT diesel	√	√	√		√	
Methanol	√	√			√	√
Mixed Alcohol	√	√				
Natural Gas	√	√				
Hydrogen	√	√			√	√
Hythane	√	√				
LPG	√	√				
Renewable diesel		√				
Diesel mix	√	√				
Biodiesel		√				
E-Diesel		√				
Ethanol	√	√			√	
Methanol	√	√			√	
Natural gas	√	√				

ICE=Internal Combustion Engine; LDV=Light-Duty Vehicle; HDV=Heavy-Duty Vehicle; FT=Fischer Tropsch; E-Diesel=Ethanol/Diesel blend

3.6.4. Spreadsheet-Based Models

All of the spreadsheet-based models reviewed here, including GREET (ANL version and CA-GREET), LEM and GHGenius were developed in Excel ™ 2003 (or earlier) and suffer usability issues in later versions of Excel ™ (2007, 2010). Operating any of these models in Excel ™ versions newer than 2003 is much slower than operating the models in Excel ™ 2003 and can cause the models to crash or become unresponsive. Several limitations result in this software behavior, including new file types, which store the spreadsheet data and macros in a different way (including named variables) and a "compatibility mode" for manipulating Excel ™ 2003 files that is not fully functional. Whenever an Excel ™ 2003 file (.xls file extension) is opened in Excel ™ 2007, the software enters "compatibility mode," in which most features work (albeit more slowly), but the system is somewhat unstable when the file is large and has macro functionality. These software issues have a significant impact on the user experience when attempting to run these models in newer Excel ™ versions. The best way to operate spreadsheet-based models is in Excel ™ 2003 or as a Macro-Enabled Workbook in Excel ™ 2007 (with the understanding that the file will run more slowly).

Due to the software difficulties discussed above and the need to maintain a life cycle model over time, including revisions to inputs and model structure, a relational database structure is the best framework for a life cycle model. Databases are more flexible and easy to manipulate and can provide greater transparency to the user about the model assumptions and calculations. Ideally, the database structure would facilitate scrutiny of the life cycle inventory data driving the analysis, as well a transparent, spreadsheet-based interface that allows a novice user to manipulate the database with confidence. The BioGrace model uses database methods (look up tables) to manage life cycle inventory data in a consistent structure and enable the selection of life cycle components as appropriate for the fuel pathway. The user should feel confident about the software's behavior and not be forced to deal with compatibility issues and error messages during normal operation.

3.7. Conclusions on Model Attributes

A review of fuel LCA models finds differences in their usability. In general, fuel LCA models perform the same calculations to address their primary objective. Models differ in fuel pathways, vehicles, and vehicle fuel combinations evaluated. LEM also includes additional exogenous calculations. The following observations and recommendations apply to the models reviewed here.

Table 3.6 summarizes the key attributes of the models/analyses reviewed. Model documentation, usability, accuracy, pathways included, vehicle types, co-product treatment, and geographical focus are key attributes when comparing life cycle models. Of the models analyzed, each has some areas that are well-addressed and some limitations. The JEC analysis is well-documented and easy to follow. It includes numerous pathway options and a sophisticated approach. The model is complex and considers numerous factors.

GHGenius is also well documented; it is a complex model with numerous pathways and vehicle options. GHGenius focuses on Canadian fuels and is of limited use in the European or U.S. context. However, because the user can modify any input parameters, the model can be changed to fit another region. GHGenius has the advantage that, because it is based on a spreadsheet, it allows the user to not only change inputs, but also to discern how these changes affect the final results. Results are listed in a logical, easy-to-follow manner.

Table 3.6 LCA Model Key Attributes Summary

Study	GREET	EPS RFS2	JEC	LEM	BESS	GHGenius
Model Platform	Spreadsheet plus GUI for default model GREET	GREET models posted on EPA website	No user-input; only analysis results reported	No user-input; only analysis results reported	User-input software tool	Spreadsheet
Documentation	GREET1.5 documentation and fuel reports Pathway documents for CA-GREET Many papers and reports in support of GREET pathways	200 pages in regulatory impact analysis plus files on EPA website	Reports are well-documented. Supporting spreadsheets with input data. Calculations are easy to follow in report outputs.	Some assumptions well-documented in report, but some final results not published online	Summary report shows assumptions, easy to follow. User's Guide also a good resource.	Spreadsheet contains assumptions & values. Reports downloadable for members of 'forum'.
Transparency of Calculations/ Assumptions	Calculations only in spreadsheet. Not easy to follow.	Same as GREET	Relatively easy to follow in report	Assumptions and equations given in report	Calculations not shown in summary report /user's guide	Spreadsheet not easy to follow, but can be traced
Inputs / Modeling Variability	User can select various assumptions in spreadsheet or input some values in GUI. GUI is not useful for detailed analysis.	Same as GREET	No user input capabilities; only report is available	No user input capabilities; only report is available	User can enter inputs on corn production, ethanol refinery, cattle feed, digester	Spreadsheet has defaults but user can easily change inputs
Availability	Publicly available	Publically available	Model not available; reports online, spreadsheets with intermediate calculations	Model not available; reports online	Non-commercial model use free. Commercial model use with license.	Publicly available

Study	GREET	EPS RFS2	JEC	LEM	BESS	GHGenius
Usability	Understanding spreadsheet calculations is difficult; cannot modify of all input. parameters with GUI. Macros manipulate data, which makes inputs more difficult to follow	Model inputs same as GREET. Finding supporting data is challenging.	Reports are easy to navigate and well-organized.	Not available to public. Similar structure as GHGenius.	Easy to use. Summary spreadsheet with results	Relatively easy to use and understand but calculations are based on macros, which are difficult to follow.
Outputs	WTT results, per MJ. TTW results, per mi. WTW results, per mi No disaggregated results by pathway component. CA-GREET results are disaggregated by inspection with considerable effort	Outputs for biorefinery entered into EPA LCA spreadsheets. Data management is inconsistently structured.	WTT (broken down by lifecycle step), TTW, WTW per MJ and per mile. Many pathways and sub-pathways evaluated. Results are disaggregated by lifecycle step.	In theory, WTT, TTW, WTW per MJ and per mile for each pathway. But the report only lists a partial set of WTT results.	WTT g CO_2e/MJ corn ethanol, broken down by lifecycle step	WTT (broken down by lifecycle step), TTW, WTW per MJ and per mile. Some results only for fuel blend pathways
Sensitivity / Uncertainty (S/U) Analysis	Stochastic simulation tool; model contains > 700 distribution functions, 4 sampling methods	EPA performed sensitivity analysis.	Some values reported as min/max; "most probable" value used in calculations	Discussion of parameters with greatest uncertainty No S/U analysis	Sensitivity analysis reportedly included in model, but not found during user testing.	Sensitivity and Monte Carlo analysis included in spreadsheet.

LEM is a very detailed model. Its supporting documentation provides references for each calculation, assumption, and emission factor used in the model. It is an excellent literature review and source of emission factors and calculation methodologies. However, the final report is still in draft format and the model has never been fully completed. The report is very lacking in actual calculations and results. Therefore the model cannot be used to look up carbon and energy intensity values of biofuels.

BESS is a user friendly model for corn ethanol WTT emissions with a focus on the U.S. "corn belt," i.e., the Midwest. The user can easily change inputs and compare scenarios. The limitation of the model lies in the fact that it only includes a single pathway.

3.7.1. Documentation

Several approaches are taken to WTW model documentation. JEC, GHGenius, and BESS all maintain comprehensive documentation that describes all model inputs in a consistent manner. The reports are relatively up-to-date. Comprehensive GREET documentation has not been completed since version 1.5 (Wang 1999). The documentation for CA-GREET details the calculations for specific fuel pathways but defers many of the inputs to the GREET model. The EPA's documentation of GREET inputs also focuses on the factors that affect the analysis but provides little to advance a comprehensive explanation of model inputs.

However, ANL has released many reports and published papers in LCA journals documenting specific fuel pathways or modifications to GREET. This approach has the advantage of providing a level of peer review to the analysis.

Documenting the assumptions and inputs to the fuel LCA models is critical for most of their intended applications. The effort involved in documentation is extensive and difficult to maintain. Yet funding for documentation may not rise to a deserved priority for the agencies and stakeholders involved in the fuel LCA area. Nonetheless, we stress the following recommendations:

- Documentation for fuel LCA models should be complete and up-to-date.
- EPA and ARB documentation is in support of their regulatory process and should not be considered documentation for the models they employ. However, because these agencies use various models, they should find mechanisms to assure proper documentation of the models they use: GREET, FASOM (the Forest and Agricultural Sector Optimization Model), FAPRI (the Food and Agricultural Research Institute model; from Iowa State University) and GTAP and their applications to fuel LCA.
- Consider a documentation effort such as the EPA's AP-42, where the documentation scope and format is consistent, but the task can be distributed among a number of collaborators.
- Include units that allow for use in both SI and English units to facilitate cross model comparison.

- Many of the parameters in fuel LCA models are poorly documented; some are even poor estimates. In particular, inputs for sensitivity analysis, agricultural chemicals properties, and fuel properties should be better documented.[24]

3.7.2. Usability

Fuel LCA models have executed a number of strategies regarding usability. These include user interfaces (GREET, BESS), inputs sheets (GREET, GHGenius), and structured calculations (JEC).

Only the JEC approach maintains a structured database that allows for a consistent set of calculations to be applied in a flexible manner. The calculation approach in GREET and GHGenius is based on a structured set of calculations. However, the calculation structure is not uniformly applied. In GREET especially, data inputs buried in cells and exceptions to calculation steps make the model more difficult to understand. Ideally, the analysis would be available in a database structure that would allow for either spreadsheet or database manipulation of life cycle inventory data.

The challenge of maintaining a user interface with appropriate detail and functionality needs to be considered within the scope of such a software design. Therefore:

- If developers provide a user interface, its scope should be limited to functions that the developers can reasonably and cost effectively maintain.
- Spreadsheet access to model features such as the life cycle inventory database, input data, and output results should be maintained.
- Models should show understandable parameters such as:
  - Inputs in units of commerce such as yield in L/barrel oil or L/tonne of feedstock, and electric power usage in kWh/L of fuel produced
  - Break out of energy inputs and emissions by fuel cycle step
  - WTT results and fuel carbon in the same units (g/MJ)
  - Account for total fuel cycle
    - Include energy in biomass
    - Track biogenic carbon separately from fossil carbon
- Publish LCI of key fuel cycle components
  - Natural gas, ammonia, diesel fuel, residual oil, etc.
- Perform cross comparison among fuel LCA models

[24] The JEC WTT effort relies on a database for LCI values. Therefore, the data for chemicals is documented by reference.

4. Fuel Life Cycle Analysis Issues

Many issues affect the LCA results for biofuels, petroleum fuels, and inputs to the fuel cycle. Feedstock and fuel input parameters are subject to regional and plant-to-plant variability and variability in data quality. Key biofuel issues include agricultural practices, soil carbon storage, methane emissions, nitrous oxide emission and soil carbon storage. The treatment of the co-products and emission effects of indirect activities remains an issue with all fuel pathways. Other factors are related to the approach taken in performing the LCA calculations. Determining average or marginal energy carriers, co-product credits, and region-specific emission factors have a significant impact on fuel LCA results. Uncertainty associated with the selection of input parameters that are largely left to the discretion of the LCA study team are referred to as subjective uncertainty. The organization of these issues is summarized in Table 4.1, which also notes the subsection that discusses the topic. Data sources and inputs are discussed first in the following subsections, followed by a discussion of execution and method issues.

Table 4.1. Summary of Fuel LCA Issues

Topic	Model Parameter/Attribute	Discussion
Inputs and Calculations		
4.1 Process Data	• Operator data • Aggregate statistics • Process modeling • Permit/EIR[a] • Survey	LCA studies rely on various data sources. Aggregate data, surveys, and permit applications potentially skew results. Process models are ideal systems. Permits and environmental reports often reflect highest allowable emissions.
4.2 Life Cycle Calculations	• WTT+ TTW= WTW • Farming • Feedstock transport • Extraction/refining • Co-product use/re-use • Raw product transport • Biofuel production • Biofuel transport and distribution • End use in vehicle	LCI for energy inputs are calculated in consistent set of LCA model calculations, which is a strength of fuel LCA models. Separation of use of feedstock prior to production phase is often lacking. Fertilizer calculations are less detailed. Completeness of minor materials inputs is an issue.
4.3 Life Cycle Inventory Data	• WTW calculations • Fossil fuel used in production • Fertilizers • Chemicals • Catalysts • Materials • Transportation distances • Details of Co-products	LCI inputs are only as good as the process information provided. Mass-balance data for production is often unavailable or has gaps. Co-product details are more difficult to separate if multiple uses are identified.

Table 4.1. Continued

Topic	Model Parameter/Attribute	Discussion
Biofuel Issues		
4.4 Carbon Balance	• Biogenic carbon neutral • Soil carbon flux • Carbon sequestration • Farming practice	Treatment of biogenic carbon and farming practices directly affect the carbon storage rate and fuel use.
4.4.1 Nitrogen Balance	• N_2O formation • N leaching • N carry over from crops • Manure application • Nitrogen fixing crops • Effect of N on carbon storage	N_2O emissions are one of the largest sources of GHG emissions from biofuels. Release rates vary widely among soil types and agricultural conditions. Inventory of atmospheric N_2O does not match estimates from anthropogenic sources indicating higher N_2O conversion rates.
4.5 Modeling Issues	• LCI data • Calculation recursion • Regional detail	Spreadsheet LCA models calculate endogenous LCI data for most process energy inputs such as electricity. The spreadsheet structure becomes complicated and features such as regional detail and process specific analysis versus average analyses are difficult to execute.
4.5.2 System Boundary	• Direct energy inputs • Consumable materials • Labor • Equipment manufacture andrecycle • Vehicle manufacture and recycle	Primary interest is in direct inputs and land use conversion. Vehicle and equipment emissions are less than 10% of the fuel cycle total. These are more important with equipment intensive technologies such as BEVs with solar photovoltaic recharging. Choice of different and arbitrary system boundary could also lead to significant truncation errors in life cycle emissions estimates.
4.5.1 Scenario	• Average • Marginal • New technology • Predictive • Shock for iLUC (Section 5)	Approaches to average and consequential LCA depend on choice of baseline time, trend and market data for fossil fuels, predictions of future production of biofuels including yields, land availability, etc.
4.6 Co-product allocation	• Allocation • Substitution • Hybrid • Consequential LCA	Significant range in LCA results and choice of allocation method ultimately favors one processing option over another.
4.7 Vehicle Energy Use and Emissions	• Vehicle drive cycle model • Model vs. real world data • Vehicle CH_4 and N_2O emissions	Operating data on fuel efficiency are difficult to collect and vehicle options are difficult to compare.

[a] EIR = Environmental Impact Report

4.1. Process Data

The underlying data supporting fuel LCA calculations are the usage rates, modes of production, leaks, and other parameters affecting the release of GHG constituents. These data vary among fuel LCA studies due to process and regional variation, aggregation approach, and error.

Generally, data inputs are based on a range of sources, which almost never were aimed at supporting fuel LCA calculations.

The difficulties associated with collecting and using process data sources are summarized in Table 4.2. In general, operator data are not publicly available and companies carefully guard their process performance data. Comparing performance parameters for currently operating commercial-scale fuel plants with new technology is usually difficult, because cutting edge conversion technology is usually at the pilot plant stage. Estimating commercial plant input parameters from pilot scale data involves some degree of speculation. Additionally, permitting documentation and equipment design data may not reflect actual operating conditions, for the reasons listed in the table.

Table 4.2. Challenges with Fuel LCA Data Sources

Data Source	Issues
Operator data	• Data are not available to public and plant operators are reluctant to reveal information that might provide competitive information • No commercial plant data for new technologies
Performance guarantee	• Data are not readily available • Guarantees may overstate energy usage to assure performance to specification
Engineering design	• Operating experience may differ from design • Difficulty in converting engineering specifications to LCA inputs
Permit application/ environmental impact report (EIR)	• Permit and EIR values are often intended to represent maximum release rates • Operating parameters are often aggregated and obfuscated to protect proprietary data • Data are difficult to convert to LCA inputs.
Government statistics	• Statistics are collected for reasons other than fuel LCA • Data are often aggregated with many assumptions such as conversion of material cost to consumption. Original source of data is difficult to find • Errors and misinterpretations are embedded in aggregated numbers
Design study	• Designs often based on idealized process configurations • Study participant may have no real world experience • Data inputs for design are difficult to obtain
Life cycle analysis study	• Information may be second hand, unit conversion errors, old technology, analysts limited real world experience

4.1.1. Biofuel Production Inputs

The key inputs for biofuel processing (biorefining) include conversion yield, process inputs such as combustion fuel, electric power, hydrogen, chemicals, co-product yields and fugitive emissions. Life cycle GHG emissions from the biorefinery largely depend on the type of fuel burned for process heat, heating requirements, electric power consumed or exported and the local grid resource mix, and co-products. The treatment of synthetic fuels with gasification systems is slightly different when the combusted process fuel and/or hydrogen consumed are derived from the synthesis gas produced from the feedstock.

Emissions from feedstock production depend on the conversion to fuel yield and the life cycle of the feedstock. The main biofuel feedstock parameters include:

- Agricultural energy
- Fertilizers, pesticides and N_2O releases
- Feedstock conversion yield

The performance of biorefineries with respect to contributions to fuel LCA results is summarized in terms of four simple parameters:

- Fossil fuel used for process heat
- Grid electric power input
- Chemical inputs
- Co-produced electric power

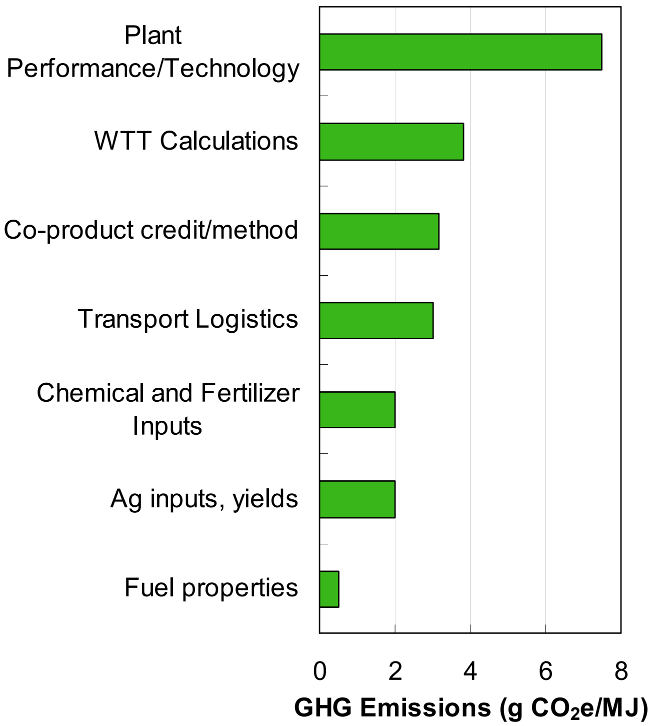
<u>Corn Ethanol</u>

Identifying the inputs for corn ethanol production illustrates the challenges in establishing an agreed-upon value for a fuel pathway. The results for the default GREET model, CA-GREET, The EPA's RFS2 GREET, BESS, and other models vary significantly, and many of the differences are not readily transparent.

Various ethanol plant technologies convert corn to ethanol. The most prominent approach is the dry mill plant, which grinds grain corn with a hammer mill to a fine powder prior to the starch hydrolysis and fermentation process. Protein, fiber, and other non-fermentable components are converted to distillers' grains with solubles (DGS). Wet mill plants process the corn fractions to gluten meal, gluten feed, germ, and corn oil in a wet process. The EPA provides a thorough explanation of the various corn production technologies and trends in efficiency (EPA 2010b). Ethanol plants continue to improve their energy efficiency via a range of technologies, primarily through heat integration, the reduction of dewatering requirements, product separation, cogeneration, and other approaches. Projections for technology improvements are often based on studies by the University of Illinois at Chicago (Mueller and Copenhaver 2009). The projections are based on performance guarantees from technology developers combined with operational data from existing ethanol plants.

Several factors lead to differences among WTW studies of corn- and starch-based ethanol as indicated in Table 4.1 with an estimate of the source of variability shown in Figure 4.1. The leading discrepancy arises from studies examining different technology options for dry mill corn ethanol. The analysis from the BESS model reflects new technology with a projected share of wet DGS (Liska and Cassman 2009, Plevin 2009). ANL's baseline results reflect the average of U.S. plants responding to a survey in collaboration with the Renewable Fuels Association (RFA). The EPA projects ethanol plant technology through the year 2022 in the RFS2 analysis, including the adoption of technologies such as cogeneration and corn oil extraction. The 10 sub-pathways for corn ethanol under the LCFS are based on both existing and new plant performance parameters (ARB 2009b).

The differences among these analyses for corn ethanol are a good example of subjective uncertainty. Scenario definitions related to plant energy consumption account for most of the differences among the results. Electric power resource type and the treatment of co-products are also key factors.



<u>GREET 1.8c.0</u>

- U.S. average ethanol plant technology, data from RFA survey
- U.S. Average transport, electricity mix
- DGS credit = 0.992 corn + 0.306 SBM + 0.022 urea
- Missing some upstream fuel cycle (WTT) for ammonia

<u>CA-GREET</u>

- Transport from Midwest to California
- Regional electricity and petroleum mix
- 1:1 corn to DGS credit
- Coal carbon content
- 10 sub-pathways
- Truck transport to blending terminals

<u>BESS</u>

- New plant technology
- Mix of dry, wet DGS
- Missing some upstream fuel cycle emissions

<u>EPA RFS2</u>

- 2022 mix of ethanol plant technology projections
- DGS credit based on FASOM analysis

Figure 4.1. Source of Variation in Dry Mill Corn Ethanol CI Results (Direct Emissions, no LUC)

<u>Sugarcane Ethanol</u>

The production of sugarcane ethanol involves agricultural production, mechanical harvest or field burning, industrial fermentation, distribution, co-generation of electricity and steam, ethanol end-use and by-products, and water recycling to irrigate sugarcane fields (Macedo, et al. 2004). Bagasse is generally used to supply process heat and electricity at the fuel plant, although some fossil fuel is used for boiler start-up. By-products and co-products must be treated. Excess electricity generated is sold back to the grid and assigned a co-product credit for displaced grid electricity, after accounting for transmission losses. The treatment of co-product power is an issue because of the allocation to sugar and ethanol and the potential use of biomass to create electric power absent biofuel production (see Section 4.6). Surplus of electricity due to the cogeneration activity is accounted for as a subpathway under the LCFS and included as zero in the default GREET model. The other product is vinasse, which is returned to the fields, condensed to concentrated vinasse syrup, or degraded in a digester. Sugarcane ethanol production produces significant vinasse. In Brazil the vinasse is returned to the fields as fertilizer. In the U.S. vinasse will likely be processed as animal feed or to anaerobic digesters. No major life cycle models or studies currently exist that account for vinasse production.

Sugarcane residue is treated as carbon neutral or short cycle carbon. Net greenhouse gas emissions from field burning include methane and nitrous oxide emissions; they contribute approximately 7 g CO_2e/MJ to the ethanol CI. Brazil is phasing out the field burning practice. Sugarcane production with and without field burning is treated as a sub-pathway for the LCFS (ARB 2009d).

Another important factor in addition to the share of sugarcane produced with and without field burning is the share of sugarcane cultivated for sugar vs. ethanol production. The split between the ethanol or sugar production affects fuel LCA results because aggregate data on fertilizer inputs are distributed between the two products. Studies usually refer to a 50/50 ratio of sugar/ethanol from mill data in Brazil.

The fuel pathway options discussed above result in a range of GHG emission results, so sugarcane ethanol GHG emission results depend on the precise pathway configuration. Switching from field burning to mechanical harvesting reduces fuel pathway emissions significantly (see ARB 2009d). Co-generating fuel plant energy from bagasse yields a much lower CI than using natural gas or coal. In addition, most sugarcane ethanol life cycle analyses simply ignore the vinasse, implying it is returned to the fields with no impact. Properly accounted for, the vinasse can have a significant impact on fuel cycle results, depending on its fate. The vinasse can be returned to the fields, producing methane emissions (positive contribution to fuel pathway results) or processed to concentrated syrup (similar to black strap molasses) and displace high value (or high CI) syrup product.

Cellulosic Ethanol

Cellulosic ethanol production includes feedstock collection/production, fuel production, including complex acid hydrolysis and sugar fermentation, and fuel transport and distribution. Cellulosic feedstock inputs include residues from crops, forests, primary mills, landscape fill, farmed trees, corn and other residues/stover, perennial grasses, waste from landfills, and other sources.

The feedstock collection and transport contribution to the GHG emission results for waste biomass depends on the biomass geographic distribution and moisture content. Geographic distribution determines feedstock transport distance, and moisture content determines the transport intensity (g CO_2e/tonne-mi), because transported water content is wasted cargo space and weight. The feedstock production and transport emissions results for energy crop feedstocks (e.g., farmed trees) depend on farming practices (farm equipment fuel use and agricultural chemical application) and biomass moisture content. In the fuel production plant, the ground up feedstock is pretreated, hydrolyzed to yield sugars, and fermented. The fuel plant input parameters depend on the feedstock type (hardwood, softwood, agricultural residues, etc.), and composition, including the quantities of cellulose, hemi-cellulose and lignin. Residue processing once the ethanol is produced varies among the fuel processes employed.

Biorefinery energy inputs vary among developers and are often proprietary as companies move into commercial phases of production. Cellulosic ethanol production co-products include electricity, mixed alcohols, and, in some cases, bio-char. All can be allocated within the LCA. Results depend on allocation method (see Section 4.6 about co-product credit allocation). Land use change impacts for cellulosic pathways are usually zero or negligible when wastes, algae, residues, and similar materials are used as feedstocks. However, cellulosic ethanol production emissions are still quite difficult to predict as current technologies rapidly shift from pilot to commercial production for different pathways.

The contribution of the first three biorefinery inputs indicated in Section 4.1.1 is assumed to be zero for enzymatic-based ethanol production. However, many other biorefinery options are under development. The co-produced electricity credit for developing technologies depends on process models that have not been validated by comparison to actual plant data. The co-product treatment of cellulosic ethanol in GREET provides an interesting outcome whereby biorefineries that produce less ethanol and more electric power achieve a lower and possibly negative CI (Section 4.6 addresses this issue).

Carbon sequestration models for biofeedstocks can underestimate actual carbon storage by perennial grasses. Several recent cellulosic ethanol LCAs have focused on incorporating new data on farming practices to evaluate carbon storage in more detail (Tyner, 2010). Inputs are commonly based on data from research plots or estimates. However, new studies have evaluated biomass energy crop production in field trials on marginal cropland. Such studies should improve input data quality and quantity.

Biodiesel and Renewable Diesel

Both biodiesel (BD) and renewable diesel (RD) pathways include farming, feedstock transport, BD/RD production, fuel transport and distribution (T&D), and vehicle use of the fuel. The tailpipe emissions from the combustion of BD and RD are assumed to be the same as those for conventional California Ultra Low Sulfur Diesel (ULSD).

Fatty acid methyl (or ethyl) esters (FAME or FAEE) are produced via the transesterification of a triglyceride (oil or fat) with an alcohol (methanol or ethanol) to yield FAME/FAEE and glycerin. The inputs driving the transesterification energy and emissions calculation include the direct esterification energy inputs (natural gas and electricity), chemical inputs, and the oil feedstock usage factor (kg RD/kg oil). The proportions with respect to biodiesel production are 10% by weight methanol consumption and 10% by weight glycerin production.

4.1.2. Agricultural Inputs

Agricultural inputs include fuel for farm equipment, electricity for farm operations, and chemical inputs that include fertilizers, herbicides, and insecticides. National Agricultural Statistics Service (NASS) data show fertilizer application and corn crop yields by state, seen in Figure 4.2. As the data show, Iowa and Illinois produce the most corn, but all states show a very similar yield on a per acre basis and a modest range of nitrogen inputs on a per bushel basis. Nitrogen is the main fertilizer ingredient for crop, farmed wood, and algae production, but phosphate, potash, and lime are also important. These inputs vary over a relatively tight range as well.

The Food and Agricultural Organization (FAO) of the United Nations maintains fertilizer statistics by country for nitrogen, phosphorous, and potassium, in a database known as FertiStat. Table 4.3 shows the FAO fertilizer application data for key crops grown in the U.S. (1998) and

Brazil (2002) in kg nutrient per hectare. The FAO data represent chemical inputs applied to the land. GHG calculations should reflect emissions per unit of harvested crop. This requires a yield factor indicating the crop yield (bushel or tons) per land area (acre or hectare).

Although the FertiStat database does not include crop yield data along with the fertilizer application data, the FAO includes average crop yield data by country, which provides the basis for converting the application yield data to units of gram chemical input per bushel or ton of crop produced, assuming the yield data is on an "applied" basis rather than a harvested basis.

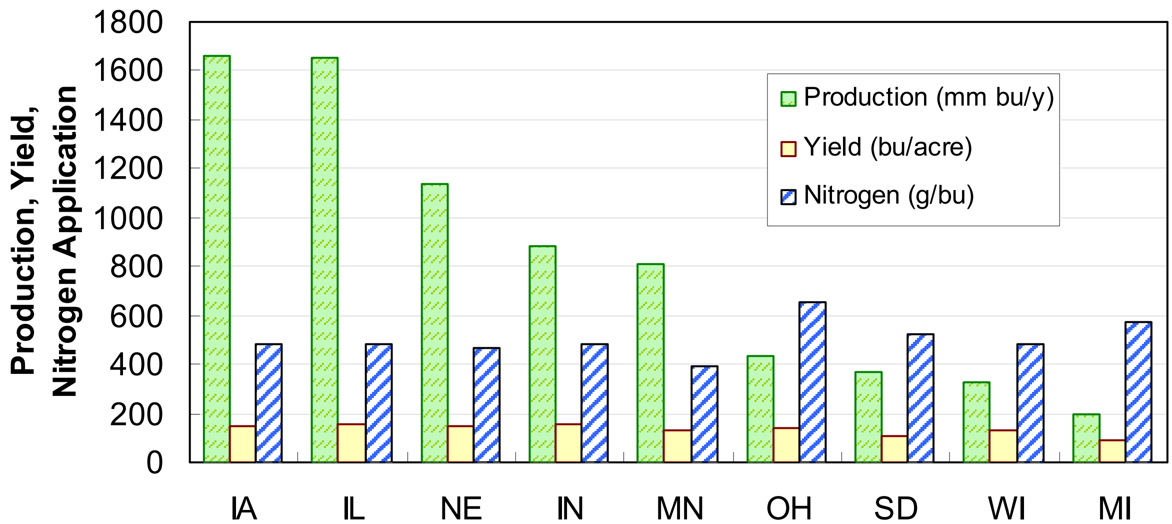
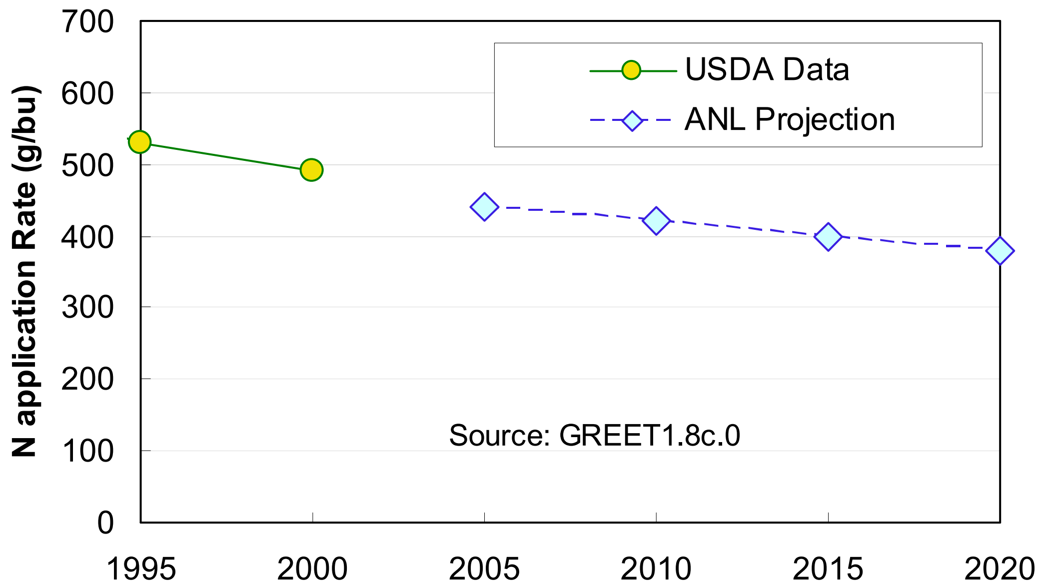


Figure 4.2. Corn Annual Production and Nitrogen Application Rate

Table 4.3. Fertilizer Inputs for GREET and FAO

Model	GREET 1.8c.0	GREET 1.8d.0	FAO U.S.	FAO Brazil	
Scenario Year	2000	2000	1998	2002	2002
Crop	Corn	Corn	Corn	Corn	Sugarcane
N	140.1	158.4	150.0	40.0	55.0
P	49.7	56.2	70.0	35.0	51.0
K	58.0	66.0	90.0	33.0	110.0
Crop Yield (kg/ha)	8,474	8,474	8,438	3,058	71,440
Application Rate	g/bu	g/bu	g/bu	g/bu	g/tonne
N	490.0	474.7	451.5	332.3	769.9
P	170.0	168.3	210.7	290.7	713.9
K	199.0	197.7	270.9	274.1	1,540

The nitrogen application rate used in the GREET model is shown in Figure 4.3. The fertilizer input parameters used in GREET are projections based on the U.S. Department of Agriculture (USDA) fertilizer application data for 1995 and 2000. The GREET nitrogen application rate projections (denoted ANL Projection in Figure 4.3) correspond closely with the FAO data for the U.S. given in Table 4.3. Fertilizer use rates decrease over time (at 1% per year) based on the assumption that farming management practices improve at the historical rate. The improvements in both crop yield and fertilizer efficiency are embedded in GREET default assumptions, and are consistent with those used in the EPA's RFS2 analysis; however, no clear documentation for the yield projections or fertilizer application rates are available.



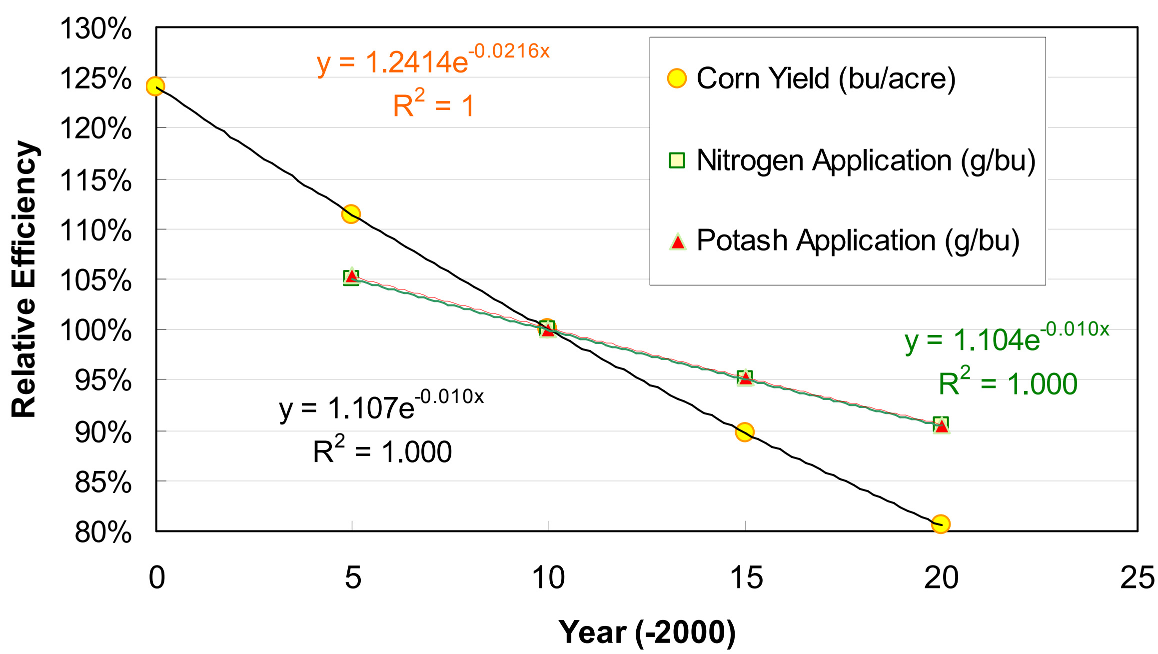


Figure 4.3. GREET projections of relative efficiency over time for corn farming

Projections for future yield and fertilizer inputs in GREET appear to be based on an exponential relationship, as curve fits of the data in GREET yield a correlation coefficient of 1.00 with four of five point fits. However, the basis for the improvements in yield and fertilizer application is not documented or tied to projections in the EPA's RFS2 analysis.

Another agricultural issue is the treatment of organic fertilizer. GREET counts the residual soil nitrogen, presumably from manure or crop rotation with soybeans, in the calculation of agricultural N_2O emissions. GREET assumes that 1.3% of the nitrogen applied becomes residual nitrogen, which is subsequently converted to N_2O (see Section 4.4.1)

4.2. Life Cycle Calculations

Energy and material inputs provide the basis for the calculation of direct emissions. These inputs are summed over the fuel cycle and combined with comparable life cycle factors for diesel, electric power, fertilizer, and other inputs. The GREET model performs most of these calculations internally and provides an adjustment for co-products. This approach is similar to the approach taken by the European Joint Research Centre and the Canadian GHGenius life cycle models (JEC 2008, $(S\&T)^2$ 2005). The key factors that drive GHG emissions are energy inputs, fertilizer application, and treatment of co-products.

4.2.1. Well-to-Wheel Summation

A well-to-tank (WTT) fuel cycle analysis of a biofuel production pathway includes all steps from farming to final finished biofuel. Tank-to-wheel (TTW) analysis includes actual combustion of fuel in a motor vehicle for motive power. Together, WTT and TTW analysis are combined to provide a total well-to-wheel (WTW) analysis. Many models and analyses present aggregated results either as one number (WTW emissions) or as WTT and TTW results. Presenting disaggregated results, including results for each pathway step and disaggregated TTW results (fuel carbon and combustion methane and nitrous oxide), elucidates the major contributors to the results and allows a third party to recreate the analysis or estimate the impact of small changes to individual pathway component results.

The functional units within fuel cycle calculations are the total energy and greenhouse gas emissions per unit fuel energy (mmBtu or MJ). Energy consumption is expressed as a unitless ratio of total energy input (including fuel energy) per unit of fuel output (Btu/mmBtu or J/MJ). GHG emissions are expressed as grams of CO_2 equivalent per unit of fuel (g CO_2e/MJ), and are referred to as the carbon intensity (CI). The GHGs considered in the analysis are CO_2, N_2O, CH_4, CO, and volatile organic compounds (VOC, evaporative and exhaust). GHG emissions from TTW portion arise from the carbon content of the fuel (g C/MJ fuel) converted to CO_2 (44 g CO_2/12 g C), plus vehicle emissions of CH_4, and N_2O. Global warming potentials (GWP) (g CO_2e/g constituent) for CH_4 and N_2O are taken from the Intergovernmental Panel on Climate Change (IPCC) global warming potential (GWP) values (IPCC 2007) for a 100 year time horizon. CO and VOC are assumed converted to CO_2 in the atmosphere, and thus have GWPs of 1 when expressed as CO_2 (fully oxidized form).

4.2.2. Transport Logistics

The transportation of feedstocks and fuels throughout the fuel cycle is accomplished via a variety of delivery modes, including trucks, marine tankers, barges, and pipelines. Energy inputs and GHG emissions depend on cargo-carrying capacity, carrier fuel type, and fuel economy.

Many biofuels require special transportation logistics due to their blending requirements, vapor management, need to avoid contamination, and marketing considerations. Both ethanol and biodiesel are currently not distributed in petroleum pipelines, primarily due to concerns over contamination with water as well as corrosion issues. These transport requirements lead to the need for a parallel delivery infrastructure.

Transport of fuels and materials are generally high volume specialty operations and no other materials are back hauled. Exceptions may apply to lower volume fuels such as vegetable oils and ethanol today; however, at larger volumes, the cargo capacity of the carrier would increase, while the opportunities for backhauling cargo would disappear.

The GHG emissions from transport are calculated in a comparable manner among various fuel LCA models. However, the effect the variation in parameters has on life cycle GHG emissions is of interest because the effect can represent several percent of the total WTW emissions as illustrated in Table 4.4.

Table 4.4. GHG Emissions from Transport Modes

Delivery Segment	Delivery Mode	GHG (g CO_2e/MJ)
Crude oil transport	1,000,000 DWT Tanker	0.8
Crude oil transport	250,000 DWT Tanker	1.2
Refined product transport	50,000 DWT Tanker	2
Refined product w. backhaul	50,000 DWT Tanker	1
Gasoline to fuel station	Truck	0.8
Ethanol to terminal	Truck	1.2
RBOB to terminal, electric	Pipeline	0.15
RBOB to terminal, natural gas	Pipeline	0.15

Note GHG emissions for electric and natural gas powered pipeline are about the same. However, the efficiency input for electric transport should be higher than that for IC engine powered compressors.
DWT = Deadweight tonnage

4.2.3. Fuel Property Data

The composition of fuels provides the primary link between energy inputs and combustion or fuel processing GHG emissions. In general, fuel combustion results in GHG emissions; mostly consisting of the carbon in fuels converted to CO_2 with traces of CH_4, CO, and VOCs. N_2O emissions are also a combustion product, generated from the nitrogen in the air and fuel (if any). Thus the carbon factor for a fuel/combustion source is typically somewhat higher than the fuel's carbon content (see Section 4.2.5 regarding the carbon in CH_4). Fuel conversion processes result in the production of fuel, solids such as char or lignin, synthesis gas, or combustion products. Principles of mass and energy balance should apply to calculations of fuel conversion processes.

Fuel properties provide several opportunities for miscalculation in fuel LCA models including the following:

- Higher versus lower heating values
- Fuel density at one state in calculation A, different state in calculation B
- Efficiency based on higher heating value applied to lower heating value feedstock
- Emission factors include combustion efficiency factor
- Moisture or ash content different in calculations A and B
- Conversion factors confused between MJ and mmBtu
- Mix and match properties from different fuels (density, heating value, and carbon content)

These issues occur in many versions of both the fuel LCA and LUC models that were reviewed. The magnitude of the error resulting from these is generally 1% to 4%, which is relatively small. However, obvious errors detract from the credibility of fuel LCA models.

4.2.4. Metrics (Inputs and Results)

Various metrics are applied to fuel LCA results in the presentation of WTW and WTT results. The presentation of intermediate results varies among fuel LCA models making the comparison, disaggregation, and uses of these values very difficult. Some key metric issues are discussed below. Many of the examples are from GREET, reflecting as much the open source nature of the model as well as challenges in reporting.

Units

Units of commerce for fuels and materials vary among industries and regions, challenging their reporting and documentation in fuel LCA models. Nonetheless, like quantities should be reported in a consistent manner (perhaps repeated in metric units).

Biogenic Carbon

The treatment of biogenic carbon is a complex issue. Several metrics are possible for biogenic carbon and these are applied inconsistently among fuel LCA models. Table 4.5 summarizes the main carbon accounting frameworks used for biofuel LCA and Figure 4.4 shows the concept graphically, comparing baseline fossil fuel with biofuel analyzed using the second method described in Table 4.5. Biogenic carbon can be treated as neutral, from the vehicle only, or all emissions counted including those from the ethanol plant. Land use emissions could also be incorporated into the feedstock production phase[25]. Biogenic carbon is treated as neutral for biofuel crops but positive for digester gas. The treatment of biogenic carbon from waste materials requires further examination due to the various alternative fates of waste materials including long term storage in landfills. With waste materials, all of the GHG emissions from the process as well as all of the emissions from the alternative fate would need to be counted regardless of the biogenic nature of the feedstock.

[25] EPA incorporates the LUC emissions into feedstock production. Biogenic carbon emissions are treated as net zero with ARB and EPA's approach.

Table 4.5. Carbon Accounting Methods

Description	Example	Comment
Carbon neutral	• Ethanol and soy biodiesel in LCFS and RFS2	• Assumes all biogenic carbon is recently removed from atmosphere. Adjustment for LUC takes into account the effect on land.
Carbon neutral with CO_2 in TTW phase	• GREET WTW results for ethanol show no C in fuel • LCFS results for dairy digester gas show C in fuel with biogenic uptake credit	• Calculates net biogenic carbon in the production step as zero but shows the carbon in fuel separately. • The approach for counting biogenic carbon is inconsistently applied for waste resources.
Count all CO_2 taken up (credit) and count CO_2 emissions throughout pathway	• Not generally used	• Shows emissions from both vehicle and biorefinery.

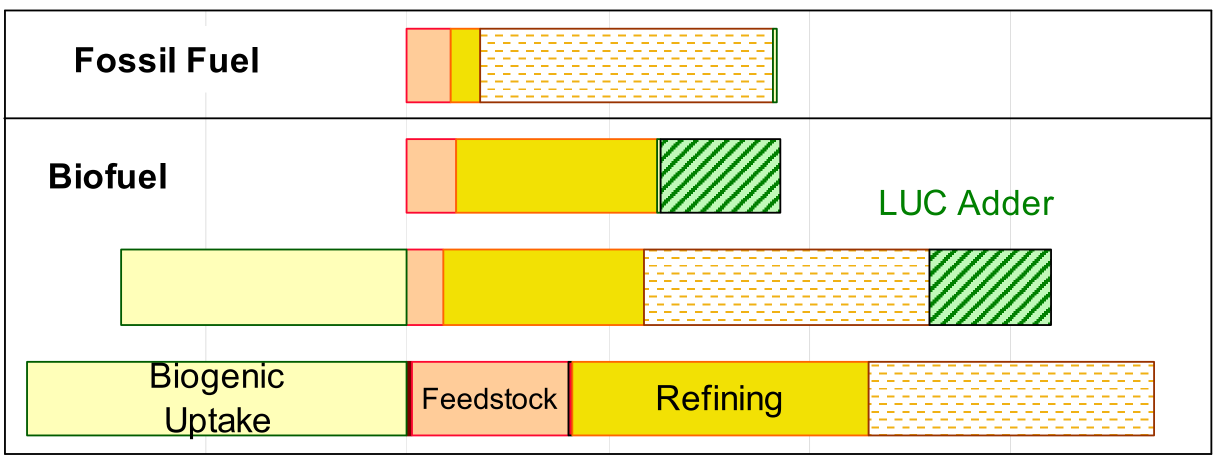


Figure 4.4. Schematic Showing Fossil Fuel and Biofuel Fuel Cycle Emissions with Fuel Carbon

<u>Model Input Values</u>

The inputs to fuel LCA models are often difficult to relate to operational data and parameters with physical meaning. Fuel LCA models tend to deal with energy inputs and efficiency while real world plant operators may deal with standard cubic feet (scf), barrels (bbl), kW, $, and many other units of commerce. The result is that the input values to models (both WTW and LUC) are often distant cousins of the physical parameter being measured. The fuel shares units in GREET illustrate this principle. Here the model input is a combination of energy input and ratio of resources. The only solution is to report both practical units and their conversion to model inputs.

4.2.5. GHG species

Global warming impacts of GHGs are "direct," caused by the radiative forcing of the gas, and "indirect," due to the effect of the gas on the concentration of other radiatively active trace gases. There are numerous parameters affecting the GWP of a gas, namely the relationship between radiative forcing and atmospheric concentration, interactions between gases, the ultimate fate of the gases, and the timeframe of analysis, since chemical reactions are time-dependent (in most cases 100 years is used).

Most fuel LCAs consider only three GHGs (CO_2, CH_4 and N_2O) and use the GWPs developed by the IPCC. The IPCC GWPs equate gases on the basis of their radiative forcing over a 100-year period, assuming an exponential decay of the gases (with multiple decay functions in the case of CO_2). IPCC GWPs for a 100-year time horizon are shown in Table 4.6 for reference.

Table 4.6. 2007 IPCC GWP Values for a 100-year Time Horizon (IPCC 2007)

Gas	GWP
Methane	25
Nitrous oxide	298
HFC-23 (hydrofluorocarbon)	14,800
HFC-134a (hydrofluorocarbon)	1430
sulfur hexafluoride	22,800

The use of 100-yr GWPs to support GHG emissions policy decisions that have implementation schedules that have most of their impact over the next 20 to 30 years has been raised as an issue. ARB discusses this issue in the Initial Statement of Reasons (ISOR) for the LCFS. The EPA has also discussed this issue in the Regulatory Impact Assessment (RIA) for the regulations to implement the RFS2. Both have concluded that the use of 100-year GWPs is appropriate for their purposes.

GHG Species Observations

The IPCC identifies GHG species other than CO_2, CH_4, and N_2O that are produced in the fuel cycle. The inclusion of these species in fuel LCA is warranted; however, the uncertainties associated with atmospheric fate and lifetimes need to be addressed. Most significant is the secondary effect of NO_x and VOC or hydrocarbon (HC) species. HC emissions have had little impact on traditional fuel LCA calculations because the carbon is converted to CO_2 rapidly in the atmosphere. However, when viewed as an O_3 precursor or NO_x scavenger, the effect of HC emissions is significant. Emission rates for fuel combustion equipment can vary by a factor of 100 and the potential conversion to O_3 or interaction with NO_x depends on atmospheric pollutant levels and weather conditions.

The inclusion of some species results in significant impacts on fuel LCA results; however, the key inputs that drive the emissions remain uncertain. For example ozone results in significant secondary GHG emissions. However, the relationship between criteria pollutants and ozone formation varies with local background pollutant conditions and weather conditions. SO_2 and fine particulate emissions are assigned a radiative cooling effect (IPCC 2001) and the calculated impact on the effective CI can be over 20 g CO_2e/MJ (Delucchi 2003) for pathways where these pollutants are significant. The LEM model examines the effect of such climate controlling gases based on IPCC's factors for radiative forcing. A significant effect may be the near term cooling associates with high sources of particulate such as coal combustion and deforestation. The effects of non CO_2 species could be incorporated into other WTW models. The effect of particulate matter from burning associated with land clearing also requires further analysis in the context of non CO_2 GHG emissions.

4.2.6. Data Uncertainty and Sensitivity Analysis

Inputs and analysis methods introduce many uncertainties into fuel LCAs. Generally, an uncertainty is evaluated using probability distribution functions (pdfs). The major areas of uncertainty in fuel life cycle assessment include:

- Emissions related to changes in cultivation and land use
- Treatment of market-mediated effects (e.g., co-products, changes in process emissions in response to changing production quantities)
- Treatment of scenario inputs (e.g., average vs. marginal)
- Carbon Equivalency Factors (CEFs) for GHGs
- Land use change impacts (see Section 5)
- N_2O emissions from agricultural processes and inputs
- Natural gas leakage from pipelines
- Feedstock resource mix
- Indirect effects on resource mix
- Vehicle efficiency

Most models present a limited uncertainty and sensitivity analysis. Data inputs for pdfs are difficult to document. Furthermore, the scope of uncertainty analysis is often truncated as a model input. For example, the pdfs associated with N_2O emissions are asymmetrical as the emissions are never zero but exceed the mean. Aggregating N_2O emissions into a single factor understates the uncertainty of these emissions.

The GREET model provides uncertainty calculation with pdfs for many of the inputs. The inputs date back to the GM WTW study (Wallace 2001), and the documentation is limited. In addition, many of the inputs are bundled and do not take into account key inputs such as natural gas flaring from oil production. The GREET Monte Carlo tool does not work with Crystal Ball™ software, which limits its flexibility.

The CA LCFS does not include an uncertainty or sensitivity analysis, except in the calculations performed with GTAP (see Section 5).

LEM provides a discussion of the model parameters that have the highest associated uncertainty. The LEM report makes some allusions regarding the sensitivity of model results to certain parameters. For example, fertilizer usage and loss – through evaporation, leaching, etc. on N_2O emissions and CO_2 uptake from fertilized vegetation – have a large effect on results; construction materials (for example for power plants and infrastructure) have a small effect on results; and emissions associated with land use change have a potentially very large effect. However, the LEM report does not present a separate section discussing sensitivity.

JEC does include an uncertainty analysis. JEC results are presented with an associated margin of error. The report documents “minimum,” “maximum,” and “best estimate” values for some parameters used in the calculations, as well as in the final results.

GHGenius can perform a full Monte Carlo sensitivity calculation and has a built-in Monte Carlo worksheet. Therefore, GHGenius performs the most sophisticated sensitivity and uncertainty calculations.

Uncertainty Observations

Fuel LCA models and studies attempt to deal with uncertainty; however, these efforts are generally rudimentary given the complexity of the inputs and analysis. Some of the key uncertainties are addressed in a limited way[26]. Uncertainty analyses should more effectively estimate the uncertainty of all of the inputs to fuel pathways. Section 2 provides a summary of the key assumptions for various fuel pathways. Typically, the following parameters are key inputs that have a significant effect on the life cycle of fuel pathways.

- Fertilizer resource mix
- Fertilizer type
- Processing energy
- Fuel production yield
- Co-product electric power
- Co-product yield
- Components of N_2O formation
  - N_2O from field application
  - N fertilizer run off rate
  - N_2O formation from run off
  - N_2O from N fixing plants
  - N from crop residue and manure
- Marginal electric power
- Petroleum production emissions

Many inputs are also scenario dependent. Uncertainty analysis often incorporates parameter or scenario uncertainty but does not combine the two. For example, by simultaneously modeling the energy and agricultural sectors one can better reflect the interaction between these.

The definition of uncertainty parameters also requires further attention. A specific case of the normal distribution for values that exist near physical limits is the truncated normal distribution. The efficiency of many different processes is commonly used in life cycle analysis. Although efficiency is constrained between 0% and 100% by definition, it is possible to have values outside of those bounds when computing a Monte Carlo simulation with a normal distribution. Figure 4.5 shows an example of a truncated normal distribution and its inputs for life cycle analysis. Imagine that this variable is defining the uncertainty – an efficiency parameter in this case. Since values for efficiency above 100% and below 0% are not possible, they are removed

[26] The uncertainty of many inputs is also asymmetrical. For example, the mean value for fertilizer run-off is 10% but the high range is many times the mean.

from the distribution as shown by the arrows at the bottom of the distribution. The underlying data and approach to developing uncertainty distributions require more attention.

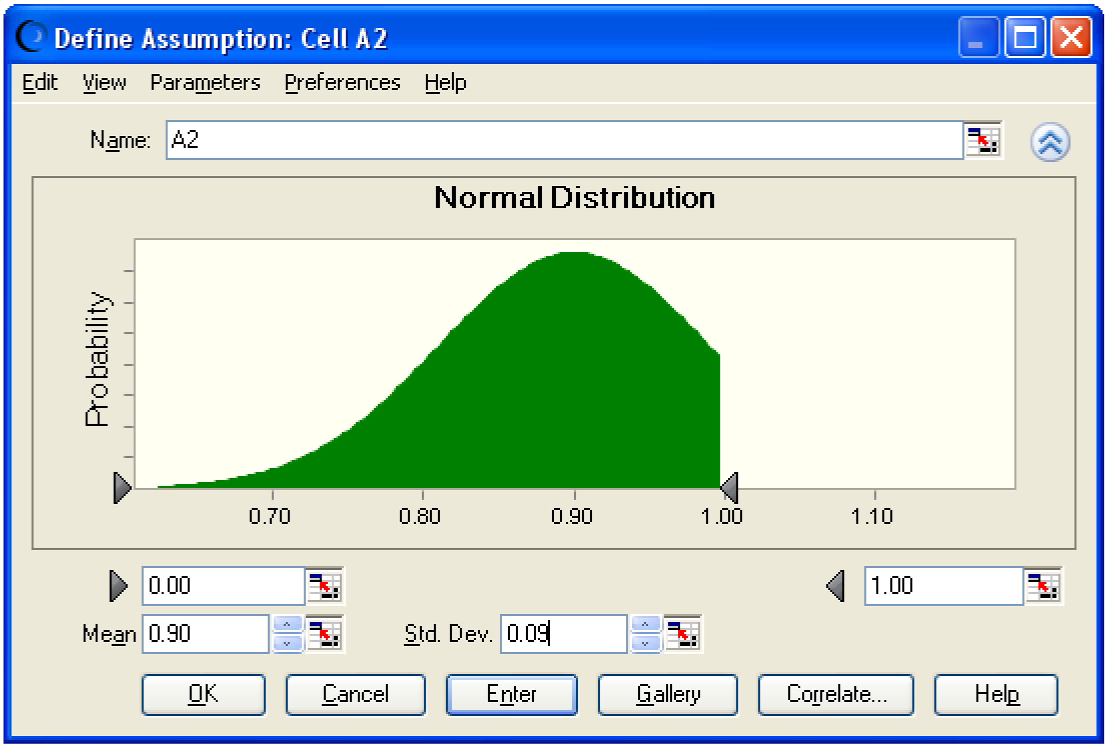


Figure 4.5. Example Input for a Truncated Normal Distribution

4.3. Life Cycle Inventory Data

Life cycle inventory (LCI) data represent the energy and emissions data associated with process fuels, transport segments, fuel pathway components, and any process or input relevant to fuel production. LCI data serve as inputs to the life cycle modeling that is discussed in Section 4.5. LCI vectors are organized as a vector (or array) of energy and emissions values. An LCI vector can represent a single process fuel or feedstock, such as natural gas used for fuel production, or it can represent aggregated fuel cycle results, such as ethanol transport and distribution. For example, the LCI array for U.S. average natural gas combusted in a stationary reciprocating engine is presented in Table 4.7 (based on CA-GREET).

Table 4.7. Natural Gas as Stationary Fuel LCI Data

Natural Gas	Recovery, Processing, Pipeline Transport	Stationary Fuel Combustion	Total
Energy (Btu/mmBtu)			
Total energy	69,898	1,000,000	1,069,898
Fossil fuels	69,649	1,000,000	69,649
Coal	1,780	0	1,780
Natural gas	62,816	1,000,000	62,816
Petroleum	5,053	0	5,053
Emissions (g/mmBtu)			
VOC	6.283	41.120	47.403
CO	11.544	342.445	353.989
NO_x	21.991	1200.000	1,221.991
PM_{10}	0.762	5.530	6.292
$PM_{2.5}$	0.496	5.530	6.026
SO_x	10.856	0.269	11.125
CH_4	128.830	368.940	497.770
N_2O	0.066	1.500	1.566
CO_2	5,229	57,732	62,960
CO_2 (inc. VOC and CO)	5,266	58,398	63,664
Total GHG (g/mmBtu)	8,507	68,069	76,575
Total GHG (g/MJ)	**8.06**	**64.52**	**72.58**

The life cycle results are organized in two vectors in this case, using the methodology of the GREET model, but the results can be represented at any level of disaggregation. The first column tabulates the WTT energy and emissions associated with natural gas recovery (extraction) and transport, processing to pipeline gas, and pipeline delivery to the point of use. The second column shows natural gas engine emission factors and the third column indicates the total natural gas LCI vector. LCI vectors can be obtained from many sources, including life cycle analysis models (including GREET), published studies, LCI databases, and are calculated based on other available LCI vectors.

Combined with the process-specific energy input (energy in/energy out) and downstream loss factors, LCI vectors can be organized in an external spreadsheet or database and used to model new fuel pathways.

4.3.1. Chemicals, Fertilizers, Materials

Chemicals, fertilizers, and other materials are also inputs to fuel production systems. LCA models include fertilizer inputs and their life cycle, while chemicals and materials are mostly excluded, except for pathways with high levels of consumption.

<u>Chemicals</u>

Biorefineries, oil refineries, and other fuel production facilities consume chemicals including urea, ammonia, and small amounts of acids (e.g., sulfuric acid) and bases (e.g., sodium hydroxide). For example, the chemical use for a dry mill corn ethanol plant is small per gallon (approximately 70 g of chemicals total per gallon ethanol) but results in thousands of tons of each chemical used per year for a commercial scale facility (100 Mgpy)[27]. Sulfuric acid and sodium hydroxide are used to clean tanks, urea is a nutrient consumed during fermentation, and anhydrous ammonia is used in the early stages of the process for pH balance and to enhance the effectiveness of the enzymes used in the slurry system. Ammonia provides the reductant for selective catalytic reduction (SCR) of NO_x emissions for oil refineries and power plants. However, many biorefineries operate below the threshold to require SCR. Table 4.8 shows some of the leading uses of chemicals for fuel production processes, their approximate life cycle GHG impact, and their inclusion in fuel LCA models.

Table 4.8. GHG Emissions Chemical Inputs for Various Fuel Processing Steps

Process	Chemical	Example Usage (g/g fuel)[a]	LCI (g GHG/ g chemical)	CI (g CO_2e/MJ fuel)
Biodiesel esterification	Sodium Hydroxide	0.02	0.5	0.2
Ethanol, dilute acid hydrolysis	Sulfuric Acid[b]	0.12	0.5	2
Ethanol, dilute acid hydrolysis	Nitric Acid[c]	0.1 to 0.2	1 to 5.6[d]	10 to 40
Ethanol, cellulosic enzyme	Cellulase	0.01	0.5	0.2
Corn ethanol neutralization	Sulfuric Acid	0.02	0.5	0.5
Corn ethanol yeast and enzyme	Yeast	0.002	0.5	0.0
Oil refinery SCR	Ammonia	0.22	3	0.005
NG Power plant SCR	Ammonia	0.19	3	0.15
Coal power plant desulfurization	Limestone	7.3	1	2.0

[a] Scoping calculations to illustrate effect of chemical inputs.
[b] Sulfuric acid usage based on NREL process model studies (Aden 2002)
[c] Nitric acid usage based on CEC ethanol study (Blackburn 1999)
[d] GHG factor is mostly associated with N_2O (IPCC 1996)

Most chemicals represent a small portion of the life cycle analysis. The effect of nitric acid for dilute acid ethanol processes potentially results in significant N_2O emissions associated with nitric acid production; although more advanced cellulosic ethanol processes are considered to be the leading candidates for future fuel production. The effect of CO_2 associated with limestone is also significant for high sulfur coals.

Chemical Fertilizers

Energy inputs associated with fertilizer production result in a significant portion of the GHG emissions associated with agriculture. The life cycle of fertilizer inputs is calculated internally in GREET or based on external life cycle data for the JEC analysis. The GHG emissions for corrected GREET values are comparable to the JEC estimates for natural gas-based fertilizer (Figure 4.6). However, coal is also an expanding resource for fertilizer production. Also the variability in fertilizer inputs and transport logistics is not well examined. All of these factors point to variability in the inputs for fertilizer that require further examination.

[27] Consider a chemical input of 70 g/gal and an LCI of 1.5 g/g for the material results in a 1 g/MJ GHG impacts.

Materials and Minerals

Both agricultural and fuel processing steps require inputs of materials such as mineral fertilizers such as potash or limestone. The life cycle of these minerals varies significantly; although the overall effect on life cycle emissions is small. Potash for example is largely shaft mined while limestone is surface mined. The inputs for the processes warrant a more detailed life cycle analysis than the inputs to GREET.

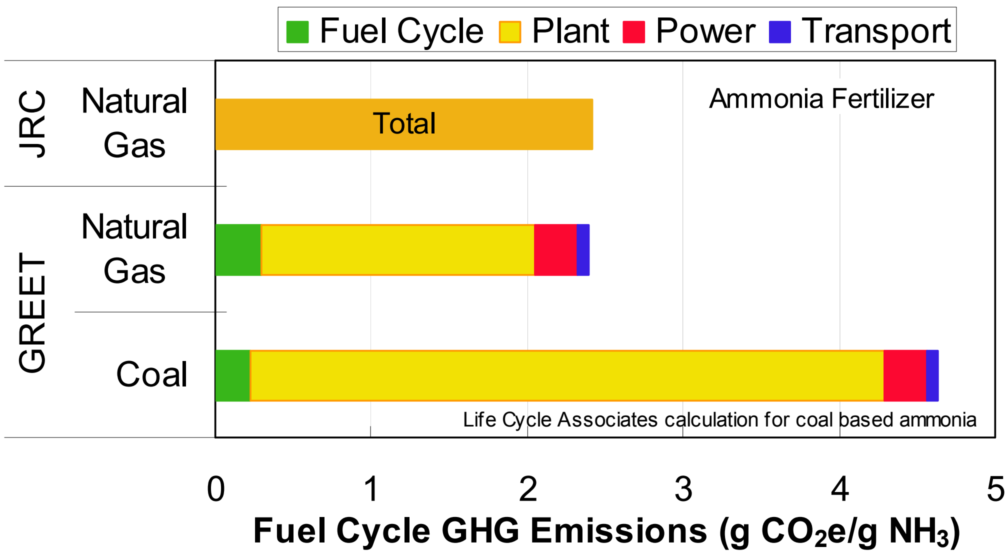


Figure 4.6. Life cycle of ammonia fertilizer

4.4. Carbon and Nitrogen Balance

4.4.1. N_2O and CH_4 Emissions

Crop cultivation can have significant nitrogen impacts associated with fertilizer and manure use, crop rotation, and residue use. Soil N_2O emissions are one of the most significant GHG contributors and one of the most poorly characterized sources to date. In terrestrial ecosystems, several N-species including nitrates and ammonia are nitrified or denitrified into N_2O, a potent long-lived GHG. A recent study shows microbes convert the nitrogen in fertilizer to N_2O at a rate of 3 to 5% of all chemical fertilizer (with attribution to organic sources) (Crutzen and Mosier 2007). The default GREET input for N conversion to N_2O is 1.3% of applied chemical N plus crop residue. However, Crutzen and Mosier's result relates to global scale crop cultivation, and does not segregate chemical fertilizer from manure, crop residue, and other organic sources. Thus the N conversion factor may not be as inconsistent as it appears. The Crutzen and Mosier number is a "top-down" global conversion rate rather than a per unit nitrogen applied conversion ("bottom-up")[28]. The analysis does indicate a disparity between the atmospheric inventory and prediction of N_2O from known sources. Finer data resolution is necessary to estimate the N_2O conversion accurately for specific regions.

[28] The observation that the Crutzen paper applies a top down method is often cited as an explanation for the discrepancy between the higher estimate and the IPCC and GREET default values. This difference does not explain the discrepancy between the estimates and the range in N2O emissions from fertilizer warrant further evaluation.

The Kim and Dale (2009) analysis is more focused on regional evaluations of N_2O emissions using the Tier 3 approach, which incorporates the 'highest amount' of regional sampled data. Tier 3 methods rely on actual sample measurement data and measured emissions. However, even the Tier 3 approach does not provide an analysis of indirect agricultural emissions. Integrating Tier 3 analyses with fuel LCA that incorporates indirect emissions will remain a challenge. The FASOM model repeatedly shows high N_2O emissions but the overall observation of the EPA analysis is that a different emissions factor was used for indirect and regional emissions.

The LEM treats nitrogen deposition and leaching for individual ecosystem types and estimates the associated N_2O emission rates for each ecosystem. The data in the LEM shows the uptake of N and subsequent conversion to N_2O varies by an order of magnitude depending on whether the ecosystem is N-limited. Because N_2O emissions contribute significantly to the lifecycle GHG emissions, it is important to develop region-specific N_2O factors relevant to the specific fuel pathway of interest.

Agricultural methane emissions depend on numerous factors (soil moisture, acidity, climate, agricultural practices, etc.) and can vary significantly from region to region and when considering crop displacement (LUC) impacts. Additionally, methane has an indirect climate impact by influencing atmospheric ozone chemistry, which usually results in a positive climate forcing (warming), but can lead to tropospheric ozone destruction (cooling), depending on the regional chemical regime and meteorological factors. The effect on ozone is long term and does not affect local smog. Predicting the indirect impact of climate species is extremely complicated, as it is usually done on a continental, hemispheric, or global basis using multiple linked chemical and general circulation models.

Agricultural Inputs and N_2O Emissions

Agricultural inputs and N_2O emissions were compared between the CA-GREET and JEC models for several fuel/feedstock pathways. Figure 4.7 shows N inputs and outputs in one example agricultural system and illustrates the difficulty of tracing a causal-effect relationship due to the variance of each category.

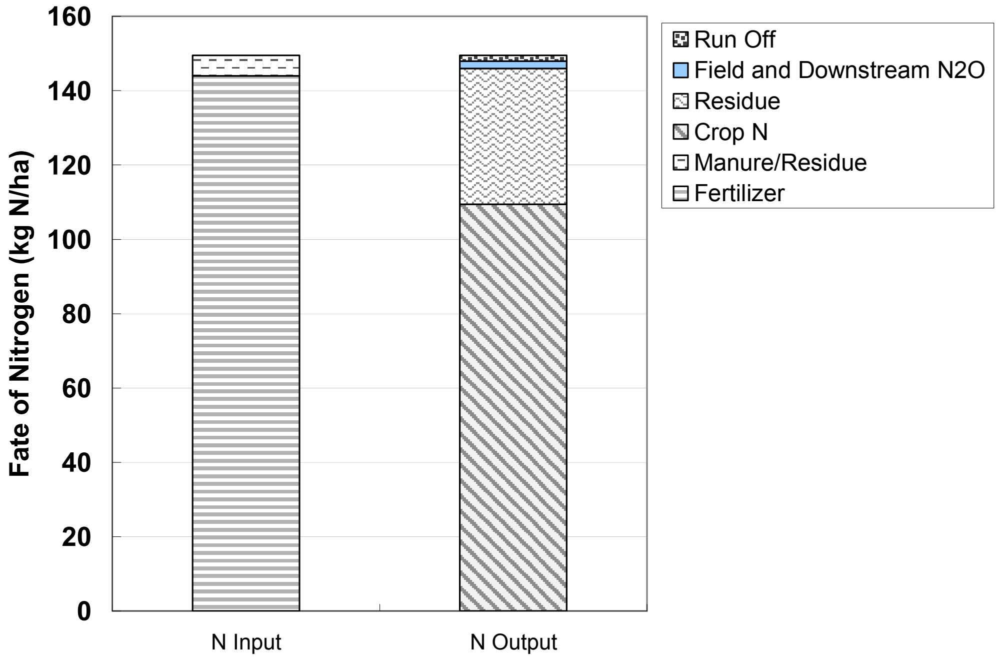


Figure 4.7. Nitrogen balance associated with corn farming and N_2O emissions

N_2O emissions from farming operations are small but very significant in the overall GHG balance because of their high GWP. It is important to note that there is a very high uncertainty in the estimation of N_2O emissions from farming. Table 4.9 summarizes N_2O parameters and issues and Figure 4.8 summarizes EPA RFS2 crop N_2O emissions.

<u>Nitrogen Conclusions:</u>

- GHG emissions associated with the production of nitrogen fertilizers and the N_2O emissions associated with agricultural practices are one of the larger GHG sources from biofuel production. Fertilizer application varies significantly by region as do N_2O emissions as well as the methods used to estimate N_2O.
- Further research is needed into the attribution of total global N_2O emissions to crop production for biofuel commodities, and also to reduce the uncertainty in the indirect emissions.
- Further analysis is needed of nitrogen-to-dry-matter ratios as a function of cultivation conditions for bio-energy production.
- Spatial analyses of agriculture will improve the estimate of N_2O emissions with increased model complexity. These more complex analyses will consider mineral N, and N_2O emissions that can vary with environmental conditions, such as temperature, precipitation, pH, and soil characteristics.
- Reduced GHG emissions are possible through improvements in practice, such as avoiding over-application of fertilizer through soil testing, nitrification inhibitors, or more efficient use of residues and tilling practice.

Table 4.9. Comparison of N_2O effects

Parameter	EPA RFS2	CA-GREET for LCFS	JEC
Fertilizer application (nitrogen, K_2O, P_2O_5) Pesticide application (herbicides and insecticides)	FASOM crop budgets based on detailed data by U.S. region. FAO FertiStat data applied to FAPRI predictions.	Fertilizer use based on USDA data with extrapolation of reduced application per unit of crop.	Estimates of fertilizer application for marginal crops. Comparable to GREET LCFS except for soybeans.
N_2O Emissions from N fertilizer production	Relies on GREET LCI factors calculated in the GREET model. Inputs are kg of N_2O/tonne of fertilizer, primarily for nitric acid as a feedstock to ammonium nitrate, 2 to 9 kg/tonne nitric acid for U.S. with highest levels at 19 kg/tonne (IPCC 1996)[a]		LBST database
Agricultural N_2O Emissions	FASOM calculates N_2O emissions based on crop type, fertilizer application, and region using DAYCENT. International N_2O = fertilizer use × 1.3%.	Field N_2O emissions calculated as a percentage (1.3%) of total nitrogen. Total N includes nitrogen applied as fertilizer plus the nitrogen content of above and belowground biomass.	Based on model from JRC-Ispra (Italy). Inputs are crop type, weather, manure rates, and fertilizer rates. Soil organic carbon (SOC) was found to be the most influential factor. Comparable to GREET values for corn, sugarcane.

[a] The GREET formula multiplies chemical N + N in biomass × 44/28, which represent the MW of N_2O and the N fraction of the N_2O molecule.

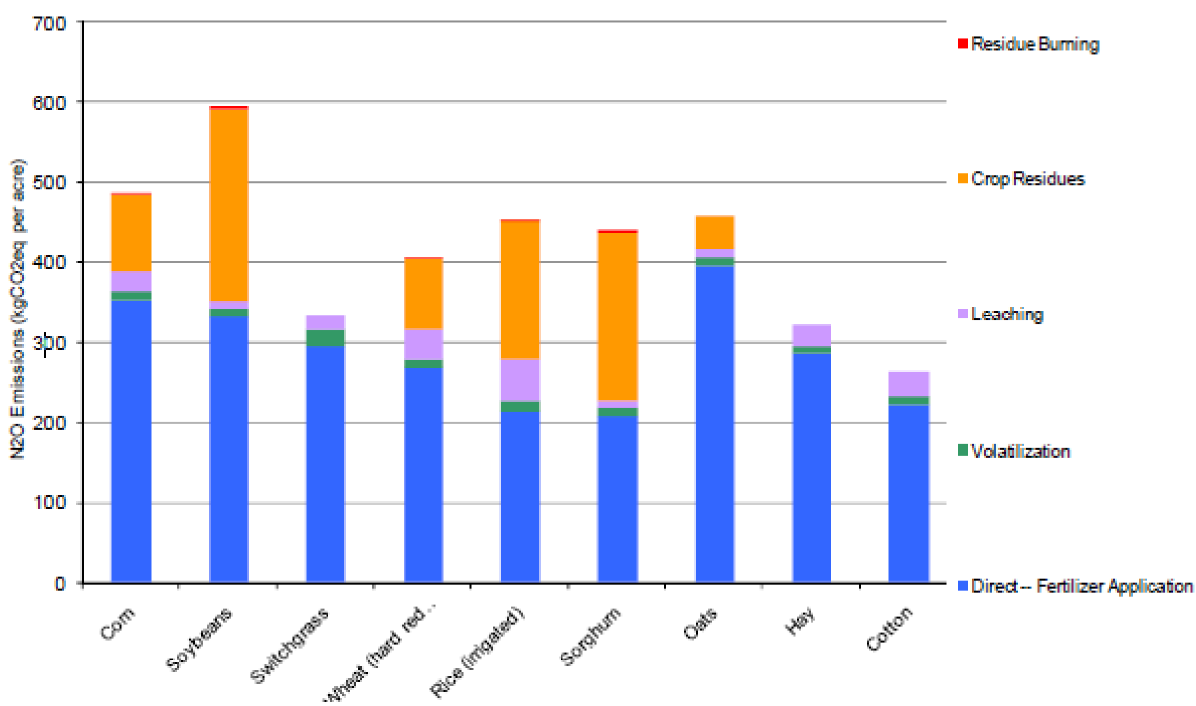


Figure 4.8. N_2O Emission Rates Based on RFS2 Analysis (EPA 2010b)

4.5. Life Cycle Modeling

4.5.1. Analysis Scope

The specified biofuel incorporates a variety of specific modeling questions and the full fuel cycle analysis often is estimated from a combination of raw mass-balance data (a portion of the LCI data discussed in Section 4.3 and where available) and default values.

The general scope includes:

- Document all assumptions, process data, and details of data collection methods
- Analysis of the process of the specific production pathway for a certain feedstock in a specific region in order to identify, and then calculate, all possible LCI vectors in the production process from WTW
- Use or develop a model or off-model for specific production pathway
- Perform model calculations and supply supporting documentation of inputs and model operations
- Include analysis of co-products for any alternative pathways in the fuel production process
- Calculate a complete WTW analysis for the LCA
- Perform additional sensitivity analysis

LCA studies can be used to support calculations of the life cycle of fuels in support of renewable energy regulatory and/or legislative initiatives for alternative fuel targets. For some pathways this is more difficult than others. If no documented life cycle pathway in a fuel mandate exists, all data need to be available for regulatory and/or legislative review.

4.5.2. System Boundary

Life cycle analysis begins with the selection of system boundaries. The boundaries indicate which energy and emissions will be included in the accounting framework and which occur outside the scope of the analysis. All life cycle fuel analyses confine the fuel pathway boundary to a manageable system to exclude unnecessary processes. Figure 4.9 identifies the system boundary for the ‘general’ biofuel pathway.

System boundary diagrams are intended to identify what components are counted in the life cycle analysis and the reference system. The system boundary diagram identifies the primary inputs and co-products and the treatment of co-products. The system boundary helps define the approach to the analysis and assure a consistent treatment for the case analyzed and the reference case.

The approach to system boundary definition varies among studies. The JEC report and ARB LCFS pathway documents identify the system boundary for each case while the EPA’s RFS2 document uses a “catch all” system boundary diagram to reflect all biofuel pathways. The EPA’s approach falls short of clarifying the process inputs and treatment of co-products between the GREET and FASOM/FAPRI analyses. This lack of definition is especially important since components of the fuel life cycle are based on macro-economic estimates, average values, and projections for marginal inputs.

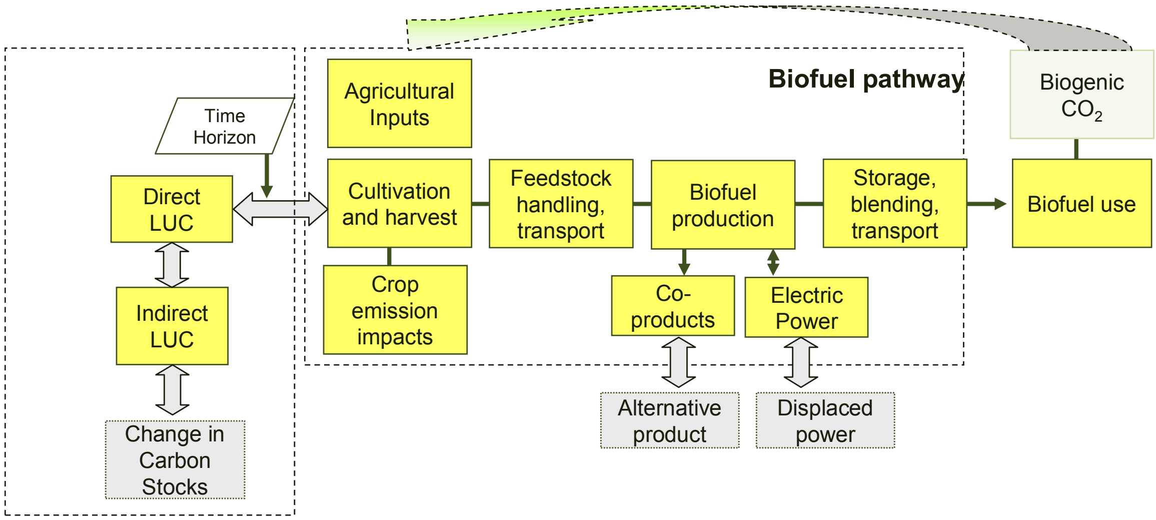


Figure 4.9. The System Boundary Diagram Identifies the Inputs and Material Flows Counted in the LCA.

4.5.3. Attributional and Consequential LCA

LUC models and their applications for different studies and policy initiatives vary considerably. In addition to differences in modeling approach, time frame, scale of biofuel use, and other scenario inputs, the modeling methodology is classified as attributional (ALCA) or consequential (CLCA) life cycle analysis (Brander, et al. 2008, Reinhard and Zah 2009). Table 4.10 below summarizes the types of questions ALCA and CLCA answer and appropriate setting for each.

The two analyses are used to answer different questions and provide different types of results, which must be interpreted correctly. ALCA models direct and upstream energy consumption and direct and upstream emissions throughout a fuel pathway (or product pathway). By definition, the analysis attributes energy and emission to the fuel pathway, which assumes the product analyzed is the dominant product responsible for the emissions and the results reflect the average total emissions associated with a unit of production. ALCA is useful for estimating the total emissions of one product (per unit), comparing similar products, or comparing a renewable product with a conventional product (petroleum) baseline. ALCA is also used to estimate total emissions associated with fuel consumption (e.g., vehicle fleet use).

CLCA is much larger in scope than ALCA and is accomplished with large uncertainty, due to the complexity of CLCA. The scope of CLCA includes total emissions from fuel production (ALCA), plus all indirect effects that cascade over time, resulting from economic effects.

Table 4.10. Attributional and Consequential LCA

Parameter	Attributional LCA	Consequential LCA
Questions Asked	• What are the total emissions (CI) produced for an average unit of product? • What is the CI for a specific fuel pathway?	• What is the consequential change in total emissions as a result of a marginal change in production?
Approach	• Calculate total direct (including direct + upstream) emissions from inputs and LCI vectors	• Model change in total emissions associated with economic response to changes in output and price
Data	• Producer data inputs; average or default values (regionally specific where provided)	• Marginal Data Inputs • Price elasticities • Product demand and supply curves
Application of Results	• Determining emissions associated with production of a specific product • Determining consumption-based emissions	• Inform Policy maker or consumer of change in total emissions and indirect effects (as much as possible) for a purchasing or policy decision
System Boundary	• All process flows within system boundary • Boundary may be expanded to capture important effects	• Process flows within system boundary and outside of boundary • Indirect effects include market, constrained resource use, substitution effect; ideally all consequences
Treatment of Co-Products	• Allocation or Substitution Method	• Substitution with second order or indirect substitution effects
Agricultural Data	• Average or marginal	• FAOSTAT; FAPRI; Other Outlook models
Model Approach	• Spreadsheet or database models with interlinked pathways and circular references	• General Equilibrium (LCA flows); Partial Equilibrium (rebound effects); Dynamic (improve understanding of marginal system effects)
Market Effects Counted?	• No (or with exogenous displacement factor)	• Yes
Non- market Indirect Effects	• Generally no	• Depends on approach

Table adapted from Ecometrica 2009

CLCA includes emissions that are within the fuel pathway system boundary and outside the boundary, anywhere in the world. Models can only accomplish an isolated view in ALCA, whereas CLCA depends on a combination of models and data sources to calculate an overall carbon intensity value for an uncertain set of variables representing a complex orchestration of economic behavior. For indirect effects, the scope is expanded to include policy choices, additional data on global markets, and the time scale of emissions including technological changes (e.g., time horizon) from an overall perturbation of global commodity markets. Policies have relied on LCA to model direct effects within the production chain at a given place in time. Indirect analyses incorporate critical choices on what model is employed, the market size, time effects from change, and other factors such as food shortages.

4.6. Co-product Credit Methods

Biofuel pathways produce a wide variety of co-products, including animal feeds and supplements, electricity and chemicals, other fuels, and soil amendments. Co-products are assigned credits in life cycle analysis to account for their value displacing other products. One of two main methods is usually used: displacement or allocation. In the displacement method, the co-product is assumed to displace a comparable product according to a displacement ratio (e.g., lbs feed corn/lb DGS) and the co-product is credited based on the CI of the displaced product. The displacement method is the preferred method to use in life cycle analysis if the method is appropriate for the fuel pathway scenario. The following guidelines apply for using the displacement method:

- Displaced product must be clearly established
- Displacement factor based on representative metric
- Co-product represents small portion of displaced product market share
- LCI data for displaced product is available, of good data quality, and based on consistent inputs (to the degree possible) with rest of LCA

The displacement method is straightforward to implement for electricity and many chemicals but the method becomes complex when applied to animal feeds. In the RFS2 Regulatory Impact Assessment (RIA) and the GREET model, excess electricity sold to the grid is assigned a greenhouse gas emission credit equal to the upstream emissions associated with the displaced grid electricity (the displacement method). The displacement method yields large co-product credits for moderate co-product electricity product (1-3 kWh/gal) when a high-CI electricity mix is displaced; the cleaner (lower CI) a grid mix becomes, the smaller the displacement co-product credit. The EPA provides a credit for electric power for herbaceous biomass such as corn stover and bagasse from sugarcane ethanol production. The GREET model provides a full credit for displaced power, subject to transmission losses (8%), which is converted into an agriculture sector net power usage in FASOM. Co-product electricity credits are calculated based on the LCI data for the assumed grid mix displaced electricity and transmission losses. The analysis should consider the causality between the fuel production and the credit, rather than simply assigning a credit to export power. This means examining total fuel production, co-product electricity (kWh/gal and kWh/yr), the grid mix through which the electricity is transmitted, and the impact of the co-product electricity on electricity demand.

The JEC has examined situations in transportation fuel LCAs that result in excessively large co-product credits that overwhelm fuel pathway emissions due to significant co-product yields. In these cases, the co-product is a dominant product. Treating it as a co-product is inappropriate, and is referred to as gearing (Larivé 2008, JEC 2008). Cellulosic or sugarcane ethanol fuel pathways are good examples of pathways with potential for gearing because they both process a lot of biomass to electricity and heat and generate substantial co-product electricity. Ethanol plants can be fine tuned to produce more electricity and less fuel, which can result in lower CI than the higher fuel yield case. In these cases, providing an electricity credit based on biomass electricity displacement is more appropriate.

Calculating the displacement credit for an animal feed product necessitates the use of a displacement factor, indicating the quantity of product displaced by a unit of co-product (e.g., DGS). The displacement factor is based on one of several metrics, including calorie content, protein content, vitamin/mineral profiles, mass, and others. The ideal displacement factor metric for animal feeds is weight gain-equivalence, in which 1 lb of feed co-product displaces another feed, equal to the feed mass needed to yield the same weight gain in cattle or swine. Unfortunately, data are not readily available relating animal feeds by weight gain-equivalence, so simpler, cruder metrics are used. Determining a displacement factor for similar feeds (feed corn and DGS or soybeans and soybean meal) is easier and more defensible than determining factors for different feed types (soybean meal and vinasse syrup).

The displacement factor inherently reflects market conditions (as discussed above for electricity) by implying that the DGS is sold as animal feed and displaces a substitute product. As biofuel production increases over time, the production of animal feeds may saturate the market, reducing the value of additional DGS as animal feed.

Figure 4.10 illustrates the potential for market saturation by DDGS, showing 2006 and projected 2015 ethanol production volumes and estimated corresponding DDGS yield, based on Energy Independence and Security Act (EISA) mandates. Annual corn ethanol production of 12 billion gallons would generate approximately 29 million tonnes (Tg) of DDGS. For comparison, current annual U.S. corn production is approximately 345 million tonnes. The co-product value of the DGS depends on the type of feed displaced. Different types of DGS are produced depending upon the processing scheme. For example corn oil extraction produces a high protein DGS. The type of feed substituted by DGS affects its co-product value (Salil). GREET 1.8d examines a range of feed rations displaced by DGS.

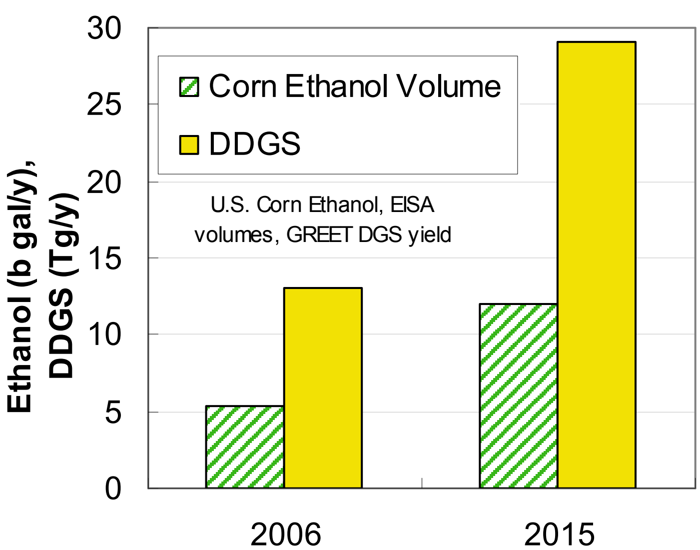


Figure 4.10. U.S. Corn Ethanol Production and Associated DDGS Yield for 2006 and 2015 (EISA)

Alternatively, technology developers are also examining systems to convert all of the solid residuals and liquids to process fuel. In this situation, the CO_2 emissions from the process fuel are treated as biogenic carbon. The LUC effect of not producing DGS would also need to be considered because the ethanol plant would no longer produce a co-product that displaces feed.

The other major method for determining co-product credits is allocation of the energy and emission between all of the products produced, based on an intrinsic property (value) of the products. Like the displacement factor, results can be allocated by energy content, mass, protein content, market value, etc. Allocation by energy content of the product streams is the most common and well-established allocation method. The method works well for fuel pathways that produce only energy products, or energy products with chemicals with a clearly defined and meaningful energy content. Applying the energy allocation method to starch- or oil seed-based fuel pathways is difficult because fuel pathways based on these crops generate animal feeds whose value is different from the raw energy (MJ) stored in the feed.

Hybrid allocations methods are often applied to seed oil biodiesel and renewable diesel pathways. The ARB LCFS biodiesel and renewable diesel pathways account for glycerin using energy allocation and soybean meal with mass allocation. When chemicals are expressed and allocated on an energy basis, a conservative co-product credit results because most chemicals have higher value use for other purposes (solvents, pharmaceuticals, nutraceuticals, biopolymers and plastics, etc.) than energy production. However, many chemical or mineral products cannot be expressed on an energy basis. Allocation on a mass basis is straightforward, and may be the best approach for animal feed co-products currently available since animal feeds are bought and sold on a mass basis. Mass is the unit of commerce.

Allocation by market value is another prominent allocation method that is well-founded in theory but very difficult to implement in practice for several reasons, including price fluctuation. In theory, the energy and emission for a production pathway should be allocated among the products based on value (market valuation), since generating revenue is the purpose of production. Unfortunately, non-ideal economic realities such as price distortions, agricultural subsidies and commodity speculation make this approach very difficult. Constant price fluctuation means that market value-based co-product credit calculations are always outdated. Most studies do not use this method. The GREET model includes market valuation for the DGS co-product credit as an option, but few users or government programs have chosen to use the method.

These allocation approaches have significant impacts on the results and, more importantly, can result in substantially different co-product credits for different processes that yield the same co-product. A co-product should have the same value and therefore co-product credit regardless of the production pathway. Allocation (by any metric) does not satisfy this requirement.

All of the co-product credit methodologies devised so far have intrinsic flaws and simplicities. To improve on the existing method requires a global equilibrium model of great complexity to model the consequential impact of a unit of co-product yield. This should be linked and harmonized as much as possible to the life cycle model used. This approach credits the co-product based on the market price of the commodity and competing goods, accounting for global economic effects, and including indirect effects. This stated, introducing a global equilibrium model, while making the LCA more comprehensive, brings its own uncertainties into the analysis.

Clearly the method of addressing co-products results in significant variation in fuel LCA models. The integration with LUC analysis, effect of different quality feed products, and principles surrounding the reference system all factor into the GHG credit. A harmonized approach needs to be developed among fuel LCA policies in order to develop consistent treatment. An inconsistent treatment among transportation fuels could potentially provide incentives to ship fuels from one region to another with no GHG benefit[29].

[29] The effect is referred to as shuffling.

4.7. Tank-to-Wheel

4.7.1. Vehicle Modeling

Vehicle efficiency and EER as a relative measure of vehicle efficiency were discussed in Section 2.3.6. The choice of EER methods is an important issue for technologies that offer efficiency advantages over conventional fuels and vehicles.

The vehicle efficiency is developed either from empirical comparisons or from modeling vehicles with identical attributes, using drive cycle models such as PSAT or ADVISOR. Typical approaches to assessing vehicle fuel efficiency include the following:

- Model clone car
- Empirical comparison of clones
- Empirical comparison by class

The use of EER assessments may vary among studies with no clear cut option satisfying all comparison needs. For example, comparisons of idealized vehicles may not reflect power train choices built by manufacturers. Even when comparing data from actual vehicles, disparities between test and actual driving/ accessory load patterns are an issue, as is the choice of comparison vehicle[30].

The ARB, for example, is providing EER adjustment to the CI of hydrogen and electric fuel pathways. At the same time, ARB needs to recognize the role of fuel efficiency for other state programs that require reductions in vehicle CO_2 emissions. Diesel, hybrid, and electric power train technologies can contribute to meeting CO_2 reduction targets; therefore, the selection of EERs is more nuanced than an idealized comparison of identical cars from drive cycle simulation models.

4.7.2. Vehicle Exhaust Emissions

The TTW emissions refer to vehicle tailpipe fuel combustion emissions. Fuel combustion emissions per MJ of fuel are independent of the life cycle analysis conducted for the WTT component and contain two main parts: tailpipe carbon dioxide (CO_2) emissions, calculated based on the fuel carbon content and fuel heating value and combustion methane (CH_4), and nitrous oxide (N_2O), which depend on the emission factors of the specific equipment and vehicle energy use.

The TTW carbon dioxide emissions are calculated using one of two methods. In the first scheme, the total tailpipe CO_2 emissions are considered based on the carbon in the fuel, and a carbon dioxide credit is assigned based on the quantity of biogenic carbon in the fuel. The second method counts only the fossil-derived carbon in the fuel. Both methods effectively consider only the fossil-derived tailpipe carbon dioxide and exclude biogenic carbon dioxide, since biologically derived fuel carbon originates from the atmosphere and the net greenhouse gas impact is neutral. The TTW CO_2 emission calculation is independent of the vehicle in which the fuel is used prior

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[30] In the case of electric and hydrogen vehicles tradeoffs between performance, weight, cost, and range lead to vehicles that may be dissimilar from gasoline options. In some instances, the customers alternative fueled vehicle choice may displace an altogether different petroleum vehicle.

to application of EER values used to compare different fuels. This approach is consistent with the IPCC guidelines.

The CH_4 and N_2O emission calculations depend on the vehicle and fuel technology. Emission factors (g/mi) are used in conjunction with vehicle fuel economy (mi/gal) and fuel heating value (MJ/gal) to calculate TTW results in g/MJ. This approach is used to calculate tailpipe criteria pollutant emissions as well. The EPA uses a multistep process to estimate CH_4 and N_2O emissions from vehicles. The results from the MOVES emission inventory model are divided by fuel usage to develop a TTW estimate[31].

4.8. Indirect Effects

Indirect effects include a wide array of impacts, including land use (Section 5), marginal fertilizer and agricultural inputs, as well as the macro economic effects associated with fuel production. However, many other indirect effects are associated with fuel production. These combined effects are grouped in Section 5.8 after the land use change sections.

[31] This approach adds confusion to the calculation of CO_2 emissions, which is simply represented by the carbon content of the fuel. Furthermore, the carbon content of the different grades of gasoline is not transparent. The MOVES model provides more detail on CH_4 and N_2O emissions from a range of vehicle model years.

5. Land Use Change Impacts

The conversion of land to crop production results in a change in the carbon stocks in the land. This change can be observed directly when new land is introduced for biofuel production or indirectly when food crops or food crop land is diverted to biofuel production. Direct emissions are difficult to estimate for land conversion because agricultural inputs and associated emissions from the production cycle can range considerably. Indirect emissions are also complex because the indirect demand for crops and resultant land conversion are influenced by many factors, including the substitution of crops and commodities.

5.1. LUC Background

Land use change (LUC) includes the direct emissions associated with land conversion to agricultural production and indirect land use change effects associated with land change (locally or elsewhere), including economic impacts induced by perturbation of global commodity markets. Estimating this change requires complex econometric modeling and estimates of conversion of land between ecosystem types, resulting in a new balance of carbon storage levels over time, with associated storage or release of carbon. LCA typically involves the attributional LCA approach described in Section 4.5; when indirect effects are taken into account, the analysis is considered consequential (Brander, et al., 2008, Tipper, et al. 2009, Reinhard and Zah, 2009).

Differences in ALCA and CLCA Approach

Application in LUC:

- ALCA attributional direct inputs and associated upstream fuel cycle
- ALCA inputs typically reflect average petroleum, natural gas, fertilizer, and electric power, although some marginal estimates are included in models
- CLCA model approaches represent wider effects of system expansion including iLUC, marginal fertilizer application, and ideally other marginal resource inputs
- CLCA models include shifts in consumer behavior including shifts in crop uses, reduced food demand due to higher price, and shifts in other economic sectors
- EPA's RFS2 analysis is considered CLCA
- JRC calculates marginal fertilizer inputs

The exchange in carbon can be induced through land conversion (or reversion) resulting from the expanded production of biofuels. The temporal and spatial pattern of this change is difficult to measure with certainty (Searchinger, et al. 2008, Fargione, et al. 2008, Liska and Perrin 2009, Geyer, et al., 2010). The source of biofuel feedstocks is often crops from agricultural land and not dedicated crops grown on new land with no agricultural opportunities. Therefore, the assessment of iLUC effects requires examining the interactions of biofuel feedstocks with the agricultural system and the resulting global shifts in agricultural activity and land use.

Two scientific papers facilitated the current iLUC global debate: Fargione (et al. 2008) and Searchinger (et al. 2008). Fargione stresses the importance of nature for carbon storage, and uses the carbon payback time to calculate different biofuel scenarios in terms of carbon savings per biofuel (or debt) - from avoided fossil fuel combustion. Searchinger examines the indirect effects of land use impacts from corn ethanol based on agro-economic modeling of the food crop. Previously, Wang and

Delucchi (2005) included iLUC in the LEM model and a preliminary iLUC factor is included in GREET through version 1.8c. Since these publications, the topic of LUC in biofuels LCA has been incorporated in the policies and regulations affecting GHG emissions from biofuels.

Table 5.1 summarizes the LUC issues discussed in this section. They are disaggregated to the affected carbon both from direct and indirect land use, the selection of displaced land, and the treatment of time dependent emissions. Additional indirect effects of biofuels production include effects on global food market impacts (e.g., the International Food Policy Research Institute – IFPRI - IMPACT model, Houghton 2003), petroleum price impacts, other biomass use, other climate effects, socio-economic effects, and even the alternatives to not using biofuels, which have not been incorporated into the iLUC analysis.

Table 5.1. Overview of Land Use Conversion Analysis

Topic	Issue	Report Section
Direct Agricultural Impacts	System boundary issues; scenario assumption (averages vs. marginal); co-products	Section 4
Land Use Change Overview	Wider system effects and transition effects; application in fuel policy; LUC models and dynamic or hybrid models; uncertainty; cropland expansion; price induced yield, trade issues, effect of co-products	Sections 5.1, 5.2 and 5.3
Land Modeling and Uncertainty	Improvements in satellite identification. Attribution of land conversion and succession to agriculture. Historical trend and econometric models; other models compared	Section 5.3 and 5.4
Carbon Stock and including in LUC models	Comparison of Winrock and Woods Hole analysis and respective policies (RFS 2 and LCFS). Impact of remote sensing data and regional carbon stock data improvements; IPCC methodology and satellite data	Section 5.5 and 5.6
Time Treatment	Duration of biofuel project, reversion of land, intergenerational equity, asymmetrical GHG impact of land conversion and reversion	Section 5.7

5.1.1. LUC Issues

The calculation of LUC presents challenges in both the estimate of carbon stocks and the release of GHG emissions as well as the prediction of land that is indirectly converted to make up for crops used for biofuel production. GHG emissions are based on default values that provide only a generic representation of carbon stocks and emissions (e.g., IPCC values). Where a specific land conversion (i.e., land type) is known, direct emission factors are calculated from spatial data combined with soil carbon data to develop a LUC factor. Additional LUC effects following IPCC guidelines include:

- Burning from fires from land clearing. Winrock has established a regional analysis of burning practices but this practice is changing rapidly on a global level
- Lost forest sequestration (e.g., 'forgone sequestration'), and
- Harvested wood products

Indirect impacts are difficult to quantify. Indirect GHG impacts from land use conversion include market and non-market effects, associated indirect impacts from agricultural chemical production and/or effects of substitution, and associated impacts on the food cycle. Cattle stocking rates in South America have a significant impact on the prediction of converted land (Lapola, et al., 2010).

Modeling issues include:

- System boundary a) ALCA: raw material extraction, production, biorefining and distribution or b) same as a) plus: land use change and market effects
- Life cycle inventory data
- Handling of linkages among sectors and regions prompts questions of how to gather and evaluate data and results
- Marginal issues in CLCA including price-induced yield, e.g., 'intensive margin' (Tyner 2010) and 'extensive margin' (e.g., the right land at the correct yield) and handling investments in land conversion (e.g., assessment of land rents)
- Baseline decisions for what to include: global markets of energy, commodities, historical trends, and policies
- Uncertainty includes choices in what to capture in the analysis and what to omit as evaluation models and methods develop and/or improve
- General equilibrium vs. partial equilibrium models

Data quality varies by biome. Some biomes pose less uncertainty in calculations of biomass cover (e.g., grassland) while other areas are much more difficult to estimate carbon stocks (e.g., forested areas) due to the scale and resolution for the analysis of spatial data. Soil carbon is difficult to analyze, since the literature presents various methods for estimates in various biomes. These estimates are based on extending calculations of carbon stock data and land cover type (Houghton, 1999, 2003) combined with ground core samples (Brown and Masera 2003, Gibbs, et al. 2007, Harris, et al. 2009), default data (IPPC) and regional soil data or maps (CENTURY model for U.S.)

- A key factor in these differences is the variability in soil moisture, temperature, and humidity calculated using the IPCC methodology for soil carbon estimates for regional estimates.
- The inclusion of the scope and scale of carbon cycle accounting for modeling is important and differs in the quantity and quality of default vs. regional data (e.g., Tier 1, 2, or 3 IPPC methodology).

5.2. Applications of LUC in Fuel Policy

The issue of LUC is addressed in a number of fuel policy initiatives aimed at both the GHG intensity of fuels and environmental impacts, including evaluation of non-GHG effects. These initiatives are addressing either the direct or indirect effects of LUC with various model approaches and levels of regional data vs. default values. Table 5.1 summarizes the topics by section covered in Section 5.

Table 5.2 summarizes these key global initiatives that address iLUC. Some initiatives are still under deliberation as to whether to include iLUC and if so, what approach should be taken. The EPA utilized Winrock carbon stock data and a variety of models for the RFS2 iLUC analysis. Alternatively, ARB employed Woods Hole carbon stock data and a different model approach to ascertain iLUC effects.

Table 5.2. Use of Models for iLUC in Fuel Policy Initiatives

Initiative	Current Policy	Models and Approaches
2007 EISA	Renewable Fuel Standard 'Final Rule' (RFS2)	FASOM, FAPRI-CARD, Winrock carbon stock/MODIS satellite data
California	Low Carbon Fuel Standard (LCFS)	GTAP, Woods Hole carbon stock
NE States, OR, WA, Others	LCFS	LUC approach to be determined
EU	Renewable Fuels Directive (RED) and the Fuel Quality Directive (FQD)	LEITAP (based on GTAP developed by Dutch Agricultural Economics Research Institute; modified nesting structure); new AFLOU model and other CGE models; final rule expected 2010
Roundtable on Sustainable Biofuels (RSB)	Stakeholder collaboration	Examining various approaches including EMPA model; draft recommendation May, 2010
UK	Renewable Transport Fuel Obligation (RTFO)	Combined Approach including current work by E4Tech iLUC analyses and best case scenarios for LUC including consequential LCA; Revision of RTFO to align with EU Directive on iLUC decision

CARD=The FAPRI Center for Agricultural and Rural Development; MODIS=Moderate Resolution Imaging Spectrora diameter (a Satellite Tool); LEITAP=Extension of GTAP by LEI (Dutch Agricultural Economics Research Institute); AFLOU=Agriculture Forestry and Other Land Use; CGE=Computable General Equilibrium; EMPA= Eidgenössische Materialprüfungs- und Forschungsanstalt, the Swiss Federal Laboratories for Materials Testing and Research

5.3. LUC Model Approaches

The assessment of direct and indirect LUC includes the tracking of biofuel feedstocks and their cascading effect on the agriculture and economic systems. Modeling the land conversion and associated GHG impacts is typically accomplished with agricultural sector models combined with spatial, regional data and associated changes to the carbon cycle. Agriculture sector models are used to assess land cover change because no easily predicted source of land and land productivity are associated with crop production. For example, in the case of U.S. corn ethanol, the supply of corn could come from additional conservation reserve program (CRP) land, corn exports, shifting from soybean to corn production, improvements in yield, or other shifts not directly associated with corn production. Thus, the iLUC effect is treated as an economic phenomenon in which changes in land use are predicted by economic (partial or general) equilibrium models that represent food, fuel, feed, fiber, and livestock markets and their numerous interactions and feedbacks.

5.3.1. Direct and Indirect Land Use Change

The distinction of direct and indirect LUC causes significant confusion. Direct emissions refer to the fluxes in ecosystem carbon and other climate species due changes in land use, such as converting grassland or forests to cropping. Direct land use change (dLUC) emissions occur on the land where the biofuel feedstock is grown and includes changes to root mass, soil carbon, and aboveground biomass.

Indirect LUC, by contrast, occurs when a feedstock displaces a crop for which demand is highly inelastic, in which case producers will replace the displaced crops by growing them on other land. Indirect impacts are price-induced effects determined by changes in spatial distribution of cropping systems between regions based on agro-economic modeling. The changes in land are combined with datasets for carbon stocks to estimate overall carbon released and the overall approach is considered a "consequential" analysis. Most studies combine dLUC emissions with iLUC emissions or treat general land cover change as iLUC, which can occur anywhere in the world.

Modeling systems like GTAP treat all land conversion as iLUC. Agro-economic models predict the demand for agricultural commodities globally and a carbon release emission factor reflects the conversion from one ecosystem type to a crop, thus lumping dLUC and iLUC factors. The combination of dLUC and iLUC becomes potentially confusing in some instances. Crops that store carbon over time in roots or forest harvesting practices result in additional time varying carbon flux.

Key LUC Issues

- Inconsistency between fertilizer inputs and co-product credits with WTW and LUC or CLCA analysis
- Economic models are based on equilibrium; actual economic effects are no equilibrium with significant price excursions
- Bundled results difficult to pull-apart
- Uncertain yield projections
- Challenge in defining land classes
- Understanding the basis for elasticity factors
- Treatment of time is user assumption with proportional effects on LUC outcome
- Evolving regional Tier 3 analysis difficult to tie to econometric predictions

For example, perennial switchgrass (*Miscanthus sp*.) can build up soil carbon in the root mass over time with a positive carbon uptake compared with row crops. However, switchgrass is considered to have relatively low annual revenue compared with corn and other food crops (Hansen, et al. 2004). Thus, modeling land displacement effects requires a more nuanced categorization of land types and carbon releases.

Another area where dLUC treatment causes confusion is the use of crop residues such as corn stover. Removal of residue does not remove any food from the agriculture system but may change the rate of carbon storage. In the case of corn stover, no-till farming practices are estimated to store carbon over time, although the overall effect requires more examination (Sheehan, et al. 2003, Kim and Dale 2009).

The removal of forest residue for wildfire reduction risk or bark beetle damage should have a dLUC effect with no iLUC. USDA is funding companies such as Cobalt that remove such damaged residue. The removal of forest material is considered carbon neutral because the material would decay over time. However, termite and wildfire activity, both methane sources, might be avoided. In addition, the rate of forest growth could also change with removal of overgrown material.

5.3.2. LUC Calculation Steps

Figure 5.1 illustrates the general iLUC approach. Biofuel production requires feedstock production, which introduces new land into production and results in a change within the ecosystem. The production of biofuel feedstocks also results in the production of co-products, which affect the agricultural system. Food and feed co-products reduce the overall demand for agricultural products. The effect of co-products is modeled simultaneously with the production of the bio feedstocks in various iLUC analyses. The change in ecosystem results in a change in carbon storage (and other GHG emissions) occurring over a period of many years. Therefore, the choice of the time horizon and subsequent applied "discount" (Section 5.7) is an important component of the iLUC calculation. The net changes are summed over time. The treatment of time-dependent emissions requires additional analyses since GHG emissions have different lifetimes and the GHG releases may occur through numerous scenarios.

iLUC is difficult to project from empirical data, if recent (<5 years) markets are included, because of the dramatic spikes in price for corn ethanol, for example. Also, taxes and subsidies are often not included in demand projections for current and future biofuel legislation mandating fuel volumes. Market predictors include elasticity factors associated with price and yields and regional supply and demand curves. Partial and general equilibrium models are employed to calculate these changes.

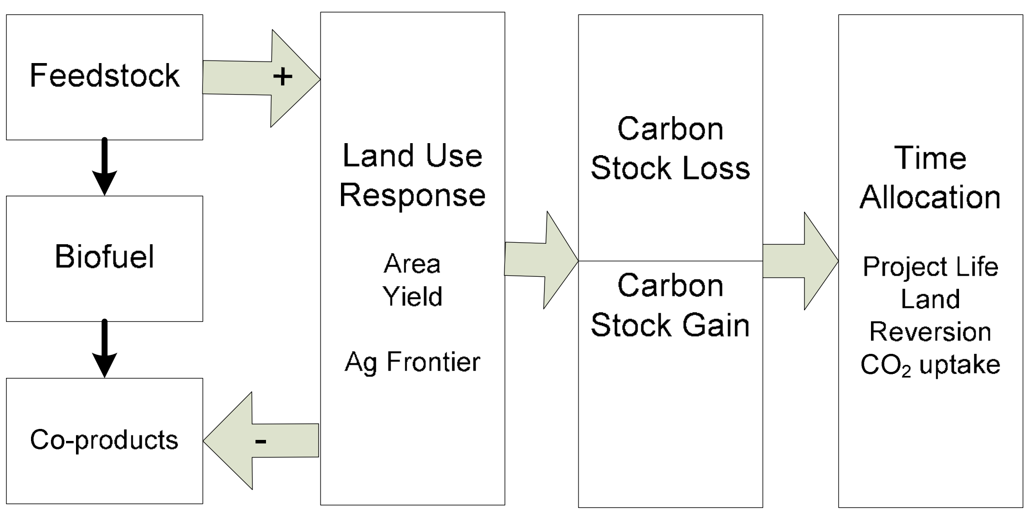

Figure 5.1. Steps in calculating GHG emissions from LUC

Overall, studies employ multiple input parameters and combined model approaches for dLUC and iLUC as shown in Figure 5.2 and generally involve a ***three-step process for LUC***:

1. The estimated proportion of increased biofuel crop demand met by increased land area (as opposed to solely increased yield)

2. Determination of system boundary, including allocation of co-products from biofuel production, the crops they displace, and the resulting land change
3. Land cover type or class (i.e., forest, grassland, pasture, etc.) and the carbon stock within a select area that is used for growing additional biofuel crops

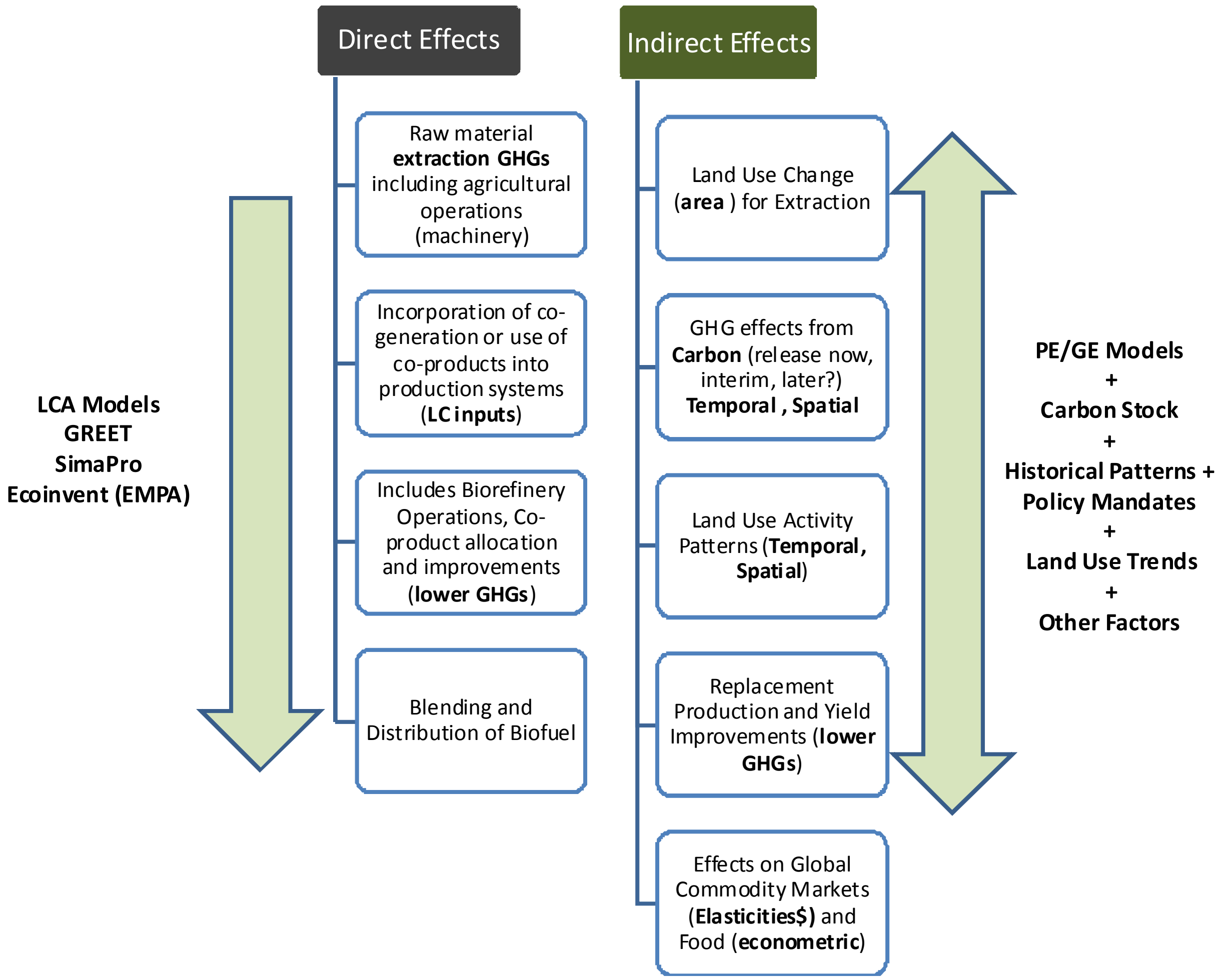

Figure 5.2. Direct (ALCA) and Indirect Effects (CLCA) Calculation Approaches.

5.3.3. GHG Releases from Land Conversion

LUC emissions are calculated from the combination of land cover change combined with emission factors associated with land cover types. The EPA and LCFS LUC analyses both combine different agro-economic predictions with bundled emission factors representing the changes in land cover.

The changes in ecosystem GHG emissions from carbon stocks are typically modeled as initial above and belowground release, foregone sequestration during biofuel production, and foregone sequestration after biofuel system reverts to native land. The emissions are treated in three phases as shown in Figure 5.3.

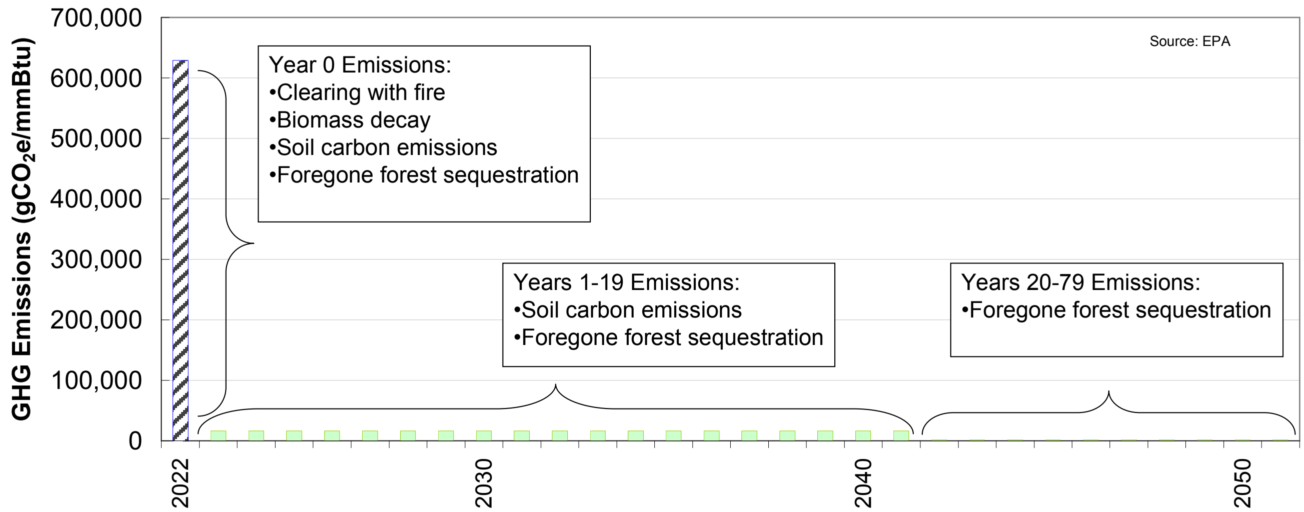

Figure 5.3. GHG Releases during LUC

The initial conversion of an eco-system to agriculture results in a large release of greenhouse gas emissions as the native land is cleared with fire and tilled. The primary fates of aboveground biomass are:

- Decay to CO_2
- Burning to CO_2 with additional CH_4 and N_2O produced [32]
- Long term storage of charred carbon
- Long term storage of harvested wood products, with some demolition and disposal over time
- Consumption of cellulose material by termites with some methanogenic activity

The dLUC emissions associated with the rest of the project life cycle result from foregone carbon sequestration in the native landscape and soil carbon emissions resulting from cultivation.

Belowground roots and other carbon are also converted to CO_2 over time, primarily through decay. This release occurs more slowly and only a fraction of the belowground material is estimated to convert to CO_2.

Depending on type and age, ecosystems store carbon over time. This carbon storage is changed when land is converted to crop production. The carbon storage is typically zero with row crops such as corn and soybeans. However, corn grown with no-till, and perennials such as switch grass, sugarcane, and palm may store carbon over time. The net change between the initial eco system and the new system is reflected by a foregone sequestration term illustrated in Figure 5.3. Perennial systems would experience a periodic release when the land is converted to other crops. After the end of biofuel production, a new eco system takes over. This conversion may be to an immature forest with a slower carbon uptake, permanent conversion to grassland, or even to other uses such as roads and development with carbon uptake. A different forgone sequestration

[32] N_2O emissions are not counted in IPCC method

term applies if the biofuel production ends[33]. GHG emissions from land conversion are summed with different approaches for addressing the uptake of carbon and release over time.

5.3.4. Other Feedstocks

Modeling the land conversion and associated GHG impacts is typically accomplished with agricultural sector models combined with spatial, regional data and associated changes to the carbon cycle. This approach applies to biofuels grown on arable land and competition with other agricultural operations must be included. A variety of potential biofuel feedstocks are not grown on arable land that would compete for other agricultural activities. Such feedstocks include:

- Wastes
- Residues: crops, forests, landscape
- Cover crops such as leguminous crops during fallow periods
- Non-arable land (e.g., degraded land)
- Harvested wood products

5.4. Econometric Models

Table 5.3 summarizes the modeling approaches used in the EPA's RFS2 and ARB LCFS LUC analyses. The following sections provide an overview of the EPA's results followed by a discussion of models and recommendations.

5.4.1. FASOM

The Forestry and Agricultural Sector Optimization Model (FASOM), developed by Texas A&M University (FASOM 2003), was used by the EPA to determine the change in GHG emissions in the U.S. for the RFS 2. FASOM is a partial equilibrium economic model of the U.S. forest and agricultural sector that tracks over 2,000 production possibilities for field crops, livestock, and biofuels for private lands in the contiguous United States. It accounts for changes in CO_2, CH_4, and N_2O from most agricultural activities and tracks carbon sequestration and carbon losses over time. FASOM estimates the cascading impacts of all crop production within the U.S., not just biofuel feedstock. The model takes into account crop shifting and reduced demand due to higher prices for agricultural commodities including corn, wheat, rice, and other crops as well as livestock.

The output of the FASOM analysis includes changes in total domestic agricultural sector fertilizer and energy use. These are calculated based on the inputs required for all the different crops modeled and changes in crop production due to increased biofuel production. FASOM output also includes changes in the number and type of livestock produced. These changes are due to the changes in animal feed prices and make-up due to the increase in biofuel production. The FASOM output changes in fertilizer, energy use, and livestock are combined with GHG emission factors from those sources to generate biofuel lifecycle impacts.

[33] All of these LUC terms are usually modeled as positive terms with a typical conversion from forest to row crops. However, the magnitude and sign varies with different crop types. Carbon release from land conversion does not occur in one year and foregone sequestration is not always constant over time. These are simplifying assumptions.

Table 5.3. Comparison of Agro-Economic Models for LUC Analysis

Model	FASOM	FAPRI	GTAP
Application	EPA RFS2	EPA RFS2	ARB LCFS
Region	U.S.	International (U.S. model is available but not applied to RFS2)	Global
Type	Partial equilibrium model of U.S. forestry and agriculture incorporating GHG emissions	Global partial equilibrium of agricultural sector	Global computational general equilibrium (CGE) with explicit treatment of land
Economic Categories	Multiple land and crops	39 economic regions	18 AEZs applied globally
Fuel demand	Demand for feedstock on agricultural system.	Demand for feedstock, modeling of blend wall[a], price effects	Biofuel shock with surrogate petroleum tax subsidy
Price/ yield response	No price response	0.074 long run price /yield elasticity	0.2 to 0.3 price/yield elasticity plus exogenous yield multiplier[b]
Area/ yield response	Yield projections for new land in U.S.	0.977 area expansion multiplier	0.66 to 0.75 area expansion multiplier
Co-product treatment	DGS and SBM treated as separate agricultural commodities	DGS and SBM treated as separate agricultural commodities	Feed co-product subtracted from biofuel feedstock requirements
Co-product power	U.S. agricultural system power modeled by FASOM with addition of new power consumption from biorefineries.	Credit for power export from biorefineries using GREET emission factors	New power for ag and biorefineries included in GREET calculations with regional specific emission factors.
Carbon Accounting	Endogenous, direct emissions factors comparable to GREET. Land emissions from CENTURY	MODIS satellite data combined with Winrock analysis of land conversion factors	Land emissions based on Winrock analysis of IPCC factors applied to AEZs

CGE = Computable General Equilibrium; AEZ = Agro-Economic Zone; DGS = Distillers Grains and Solubles; SBM = Soy Bean Meal; IPCC= Intergovernmental Panel on Climate Change

[a] The ethanol blend wall is maximum ethanol production rate that can be absorbed into a regulated transportation fuel. For example, with E10, the overall maximum blend level is 10%. Production beyond blend will not be absorbed into the fuel pool without E85.

[b] Additional factor to take into account technology improvements

FASOM uses the CENTURY and DAYCENT models to estimate the flows of nitrogen and carbon from agricultural systems and is a complex field-level model that must be calibrated to a specific site. Non-combustion GHG emissions reflect changes in soil C due to a combination of changes in tillage, changes in irrigation status (dry land and irrigated cropland have different soil C values based on the inputs from CENTURY modeling being used in FASOM), and movements of crop to pasture and pasture to crop that have taken place over time. It takes 25 years for soil C to reach a new equilibrium in FASOM (though the majority of the change happens within 15 years). Thus, shifts in land use that took place in earlier years are affecting the results estimated 10 years later.

The EPA combines FASOM output with the integrated Food and Agricultural Policy and Research Institute (FAPRI) system of models developed by Iowa State University and the University of Missouri. The FAPRI-CARD (Center for Agricultural and Rural Development) model is a worldwide agricultural sector economic model that estimates international land use changes.

Issues with Agro-economic Models

Differences:

- Elasticity value choice not transparent or tied to data independent of price
- Trends data based on econometrics and does not reflect extreme market flux in oil seeds, corn, and other agricultural products
- Econometric data not validated with biorefinery assumptions
- Acreage changes not transparent nor equated to the model shock
- Attribution to co-products, feedstock, price effects are inconsistently reported

These models capture the biological, technical, and economic relationships among key variables within a particular commodity and across commodities. A U.S. version of FAPRI is not used by the EPA, so the EPA approach combines U.S. and international models. The combination of FASOM and FAPRI adds uncertainty to the GHG analysis, and the benefits of the finer resolution of FASOM versus combining the U.S. and international components of FAPRI should be examined.

<u>Merits of FASOM Approach</u>

The FASOM approach incorporates a detailed agro-economic model with a detailed soil carbon stock and nitrogen model. This approach has been used to estimate GHG emissions from the U.S. agricultural sector. Its agricultural modeling is more detailed than FAPRI or GTAP, but the model is not accessible to broad users or applicable to LUC outside the U.S.

The calculation of agricultural soil carbon and nitrogen emissions through CENTURY and DAYCENT is a different approach than the change in carbon stocks used in conjunction with FAPRI and GTAP. Ideally, the FASOM approach would be used as an independent tool to assess LUC impacts.

5.4.2. FAPRI

The EPA uses the integrated Food and Agricultural Policy and Research Institute (FAPRI) system of models developed by Iowa State University and the University of Missouri. These models capture the biological, technical, and economic relationships among key variables within a particular commodity and across commodities. FAPRI-CARD is a worldwide agricultural sector economic model that estimates international land use changes. A U.S. version of FAPRI exists (FAPRI 2004). The EPA uses this U.S. model in combination with the international model version. The FAPRI models have been previously employed to examine the impacts of World

Trade Organization proposals, changes in the European Union's Common Agricultural Policy, and many other analyses.

The output of the FAPRI-CARD model included changes in crop acres and livestock production by type and by country globally. Unlike FASOM, the FAPRI-CARD output did not include changes in fertilizer or energy use or have land type interactions built in. The FAPRI-CARD model does predict how much crop land will change in other countries but does not predict what type of land such as forest or pasture will be affected. The EPA combined model results with data from Winrock International (Winrock 2009) to estimate what land types will be converted into crop land in each country and the GHG emissions associated with the land conversions.

Merits of FAPRI Approach

The FAPRI model provides a more detailed assessment of agro-economic impacts than GTAP. It addresses changes in crop usage for many commodities. In collaboration with Brazilian researchers, FAPRI includes a Brazilian land use model. This additional specificity should provide better predictions for the movement between cattle and crop land.

The EPA uses FAPRI land conversion analysis in combination with satellite predictions of the frontier of agriculture for each region. This approach combines a detailed agro-economic model with a detailed assessment of the marginal impacts of land conversion.

The challenge with the FAPRI system is that the model is not accessible to the public. A reduced form analysis that isolates land use by crop type and co-product and relates these to inputs such as yield effects and crop prices would be useful to enable broader use of the FAPRI analysis.

5.4.3. GTAP

GTAP is a multiregional, multi-sector, computable general equilibrium bilateral trade model used by a wide international community of modelers to assess macroeconomic effects. Changes in land use are integral to the model because it addresses trade in agricultural commodities. The computable general equilibrium (CGE) model used by the EPA is a special version of the GTAP model and has since been used by dozens of groups to evaluate iLUC; with explicit trade and agro-ecological zones. GTAP features lower resolution than partial equilibrium (PE) models, but broader market coverage. The current database is for 2006 and results are adjusted periodically to account for yield change. Current iLUC analyses incorporate this model (University of California, Berkeley, Purdue University) to evaluate land use conversion impacts of biofuel production expansion. This effort is used by ARB for the California Low Carbon Fuel Standard (LCFS). The GTAP Version 6 database divides the global economy into 57 sectors and 87 Regions. The modeler may use default elasticity values or input new ones and shock the system to determine a new distribution of land use based on trade. The GTAP economic results are then mapped to emission factors derived from carbon stock emission estimates (Woods Hole or Winrock Data, Section 5.6).

Merits of GTAP Approach

The GTAP approach has many advantages. The model manages a global database of land and takes into account the total land resources available. Partial equilibrium models may not place a limit on global land availability. GTAP also takes into account prior trade and trade barriers in order to better predict the trade of crops among different regions of the world.

The GTAP model predicts land conversion based on implied land rents. This approach for land cover prediction is fundamentally different than that used by satellite data to predict the frontier of agriculture and therefore serves as a valuable alternative method of predicting LUC.

The GTAP database can be run by other users using a general equilibrium solver. In addition, the functionality of GTAP could be expanded to include other sectors such as fertilizer in order to predict global indirect effects of biofuel use.

Several limitations of the GTAP approach include the following:

- GTAP does not contain the level of detail found in FASOM or FAPRI. Agricultural commodities are lumped into simple categories such as oil seeds (which represent soy, rapeseed, palm oil, etc.). The effects on LUC predictions of this lumping of feedstock into groups needs to be examined. The issue is more significant for the oil seeds grouping (that includes soy oil). For example, legumes such as soybeans are nitrogen fixing plants. Thus soybeans require little additional nitrogen via fertilizer application than do other oil seed crops. Oil productivity per hectare also varies significantly among the oil seeds, from 0.5 Mg/ha for soy oil to almost 4 Mg/ha for palm oil. In addition, the fraction of co-products also varies among the oil seed crops. While GTAP biofuel analyses can attempt to represent the dominant oil seed in a region (such as palm oil for Southeast Asia), modeling of the individual biofuel crops would be more transparent and accurate.
- The lack of dynamic modeling in GTAP is a common criticism (EPA 2009). For example the FAPRI model works in time steps. An important feature of time stepping in models is the changing world population and demand on agricultural products is incorporated. However, in the view of this report's authors, the importance of dynamic effects alone on LUC has not been demonstrated. GTAP can be adjusted to reflect changes in population and economic output (Tyner 2010) [34].
- The GTAP approach for land rents applies a similar calculation for livestock forage and food crops and may under predict pasture land conversion (efforts are underway to expand the analysis of pasture).
- Most of the parameters in GTAP, including elasticities, are based on econometric data. GTAP is a global CGE model with explicit trade and agro-ecological zones; thus it has less resolution than PE models, but broader market coverage.
- The economic sectors for biofuel production are "hard wired" into the model based on biorefinery data as well as economic statistics. Thus the mix of feedstock, process fuels, electric power, capital, and other inputs correspond to only one scenario for biofuel production. Other biofuel configurations, perhaps with more co-products or different process fuels, require the development of additional economic sectors. A more flexible approach, enabling the adjustment of several factors of production (not just ethanol output), would be desirable.

[34] The LCFS analysis was performed with the 2001 database. Adjustments to the database for the growth of sectors such as biofuels as other economic sectors can be accomplished by "shocking" the model. For example, in Tyner 2010, the model is adjusted post hoc to account for changes in ethanol volume, crop yield, and other economic parameters.

A study published by the Purdue team lead by Tyner, et al. (2010) challenges the corn ethanol iLUC impact calculated by ARB as 'over 100% over-estimated.' This new model work includes their own GTAP-BIO-ADV model and has the following new specifications:

- It covers production, consumption, and trade of three types of biofuels: ethanol from crops, ethanol from sugarcane, and biodiesel from crude vegetable oil.
- By-products are DDGS and oilseed meals.
- The crude vegetable oil industry uses oilseeds and produces crude vegetable oil and oilseed meals.
- The biodiesel industry uses crude vegetable oil to produce biodiesel.
- The demand for feedstuffs follows a three-level nesting structure.
- The land module handles two new land categories of unused cropland and cropland pasture.

5.4.4. GTAP Usability

Life Cycle Associates examined the GTAP model to assess its usability attributed for fuel LCA. The database is available for purchase from Purdue University and novice users can operate the biofuels models with RunGTAP interface and the GEMPACK CGE solver. Instructions for obtaining the model and solver are available on ARB's LCFS website. The project team licensed GTAP and met with ARB staff to review the operation of the model and calculation of the LCFS iLUC values.

RunGTAP is a software operating environment that provides a broad range of access to GTAP results and intermediate values. GTAP economic inputs and parameters are extensively documented from an econometric perspective. However, documentation of fuel LCA inputs is limited. The model makes use of economic sectors that are based on econometric data on some process performance data. The relationship between biorefinery inputs, agricultural inputs, fertilizer production, and GTAP econometric parameters could be more thoroughly validated. For example, cost projections for biorefineries could be converted to GTAP econometric inputs to validate the mix of components.

Novice users can use GTAP and repeat the calculation in the LCFS, although the effort requires some persistence. Several of the challenges encountered with using the model include:

- Users can change inputs to GTAP database as well as input assumptions with the interface tool. Only changes to exogenous values are appropriate. Econometric data should only be modified in a manner that is consistent with overall economic constraints. Thus, users cannot change ethanol plant yield, electricity input or other process parameters.
- Model offers several solution methods. The Johansson method provides linear approximation, which may lead to incorrect results[35]. Users should use the Gragg method.
- Running model requires understanding of syntax for shocking biofuel volumes.

[35] The Johansson method provides a rapid solution with fewer steps. This method is not intended for use with applications that assess relatively large shocks. Inexperienced model users can easily make the mistake by running the solution method that is available as the first option in the CGE solver menu.

- Documentation for non-economist users is limited. Purdue report on corn ethanol provides best explanation of model shocks (Tyner, et al. 2010).
- GHG calculations used by ARB are performed outside GTAP model. ARB should publish land cover outputs from GTAP and carbon stock assumptions in a spreadsheet to facilitate model validation.

On balance, the RunGTAP environment is relatively straightforward to use. Users can develop an understanding of the inputs and outputs and exercise the model as intended. However, the model environment does not provide access to modify the key econometric inputs that are tied to biorefinery performance. These inputs are determined by adjusting the econonometric parameters for both the biorefinery sectors and the other sectors in the model. This limitation is inherent to the nature of CGE models. A more disaggregated approach to biorefineries would allow users to make use of separate feedstock and biorefinery sectors. However, such an effort would require significant resources to implement.

5.4.5. EPPA Model

The Massachusetts Institute of Technology (MIT) Joint Program on Science and Policy of Global Change—including two centers at MIT and the Woods Hole Marine Biology Laboratory—conducted a study on land use change effects from cellulosic feedstock produced biofuels. Two approaches to LUC assessment were employed and the introduction of land 'as an economic input, in value and physical term,' was modeled using the MIT Emissions Prediction and Policy Analysis (EPPA) model (Palstev, et al. 2005). This model calculated effects for the following:

- Introduction of land supply elasticity based on observed land supply responses (iLUC)
- Considering only the direct cost of conversion (direct LUC)
- Armington trade assumptions, assumed identical elasticities across regions and economic sectors (except for regions that have less trade in the base year)
- Use of the Walsh Price index (International Monetary Fund) for two scenarios incorporating land rents: business as usual and under climate policy where later showed 5% increase in food prices and 10% in livestock prices from 2030/35 onward

The objective was to include competition between different land uses and different land types (they chose five: crops, pasture, managed or natural forest, and natural grasslands) and attempted to include land productivity variance (from economic and agricultural data for each land area and type). This was accomplished by not putting land units in rental value units (as some modelers have done). Other approaches would consider the annual return from the land without accounting for other factors, such as the distribution of actual physical land area. The MIT group modeled this effect by investigating land value and issues such as the cost of forest stock conversion to plantation timber stocks. The overall method implies that cropland from some types of 'other use' land can result from conversion of 'less' land such as unmanaged land. They use Lee, et al. (2005) land rent data and aggregate these values for all land of each type. The net carbon flux is shown in Figure 5.4.

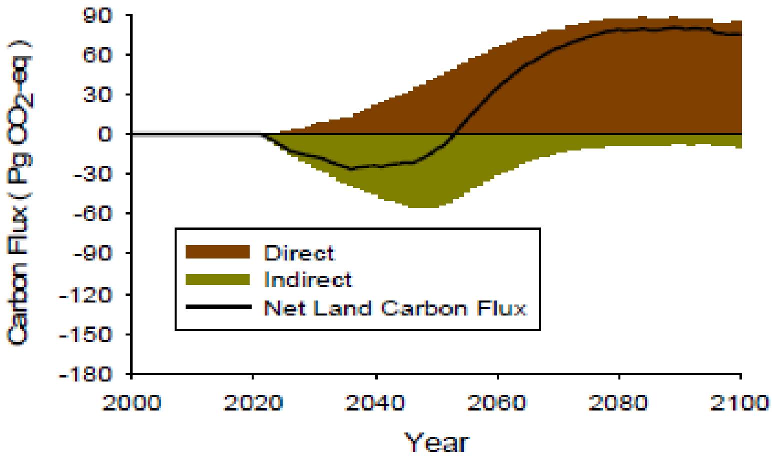

Figure 5.4. Net Land Carbon Flux, Intensification Scenario

5.4.6. Other Models

Additional model methods for LUC provide simplified approaches. Some approaches to LUC modeling select key parameters, such as yield improvement and displaced crop rather than relying on agro-economic models (Ecofys 2010). Other approaches estimate an iLUC 'risk factor or mapping' inclusive of regional specificity and feedstock variability per region (Fritsche 2009). The European Union Renewable Energy Directive provides a bonus for marginal land. Risk minimization and 'no-go zones (Dehue 2009) are intended to protect high carbon stock lands. Some of these alternative concepts appear to address the direct impacts of land conversion but are not connected to any assessment of indirect effects. Efforts to project yield improvements are also part of the analysis of LUC (Lynwood 2009).

Spreadsheet Calculators

LUC calculations can be performed in separate calculation steps addressing land cover change and carbon release. The LEM, GHGenius, and GREET models (1.8d) have LUC calculation modules with inputs for carbon stock emission factors and land cover change. The LUC impacts are calculated in proportion to the biofuel usage. This approach allows for a very transparent overview of the inputs to LUC. The additional worksheet for GREET uses GTAP land cover change results as inputs and calculates LUC emissions based on carbon stock estimates. This approach allows for greater transparency and uncertainty analysis. Other sets of carbon stock data such as Winrock's could be examined if mapped to GTAP regions.

LEM calculates LUC changes in soil carbon due to cultivation, N_2O emitted due to cultivation, and N_2O emissions related to synthetic fertilizer use and crop residue N. LEM effectively treats biofuels as if they were grown on native lands cleared for crop production. The current version of LEM does not address the market aspects of LUC.

5.5. LUC Results Comparison

5.5.1. ARB LCFS

The iLUC method incorporated into the LCFS for California is based on the ARB GTAP model approach combined with Searchinger, et al.'s (2008) dataset on carbon stock from Woods Hole incorporated by the University of California Berkeley. Multiple parameters were varied to develop a range of results with an estimate of 30 g CO_2e/MJ for corn ethanol. The distinctly higher results of Searchinger, et al., for example, result primarily from the exclusion of DGS co-product effects and yield improvements. Elasticity values, particularly for yield projections, depend on the particular crop and the respective agro-economic zone (AEZ). The sensitivity analyses by ARB included an analysis of a range of GTAP elasticity factors. The ranges were difficult to establish based on empirical data.

5.5.2. EPA RFS2

EPA used the FASOM and FAPRI models to estimate the changes in crop acreage in domestic and international markets. FASOM estimates GHG emissions in the U.S. with economic and GHG calculations internal to the model. International land changes are modeled using FAPRI and then GHG emissions are calculated separately. This section describes the EPA results and the details of the models and other analyses are discussed in the following sections.

Key Features of the EPA Analysis

- Direct combustion and upstream fuel cycle at biorefinery based on GREET emission factors
- Vehicle emissions based on MOVES model although a simple correlation to the C in fuel plus vehicle CH_4 and N_2O would accomplish the same result
- EPA performs consequential LCA combining dLUC and iLUC from agriculture sector with other indirect effects
- Fertilizer inputs based on FASOM plus FertiStat and FAPRI results, thus GREET fertilizer and agricultural inputs are not used
- Carbon stock changes for U.S. predicted by FASOM
- International carbon stock changes from FAPRI with Winrock carbon stock factors

Figure 5.5 and Figure 5.6 show the life cycle results for the EPA's final RFS2 analysis. These results reflect the 30-year time horizon (Section 5.6) for fuels that are candidates within the conventional, advanced biofuel, and cellulosic ethanol categories. The results are shown on a per mmBtu basis rather than the total emissions over a 30-year period to facilitate comparison with other studies. The EPA examines several scenarios and the ones shown here represent an illustrative set to identify the key features of the analysis.

The EPA groups the traditional WTW emissions, excluding fertilizer application and N_2O, in the fuel production, transport, and vehicle emissions. These emissions are calculated with the GREET model[36]. The balance of the emissions corresponds to the U.S. and international agricultural inputs, changes in rice and methane, and carbon stock changes from FASOM and FAPRI.

[36] Vehicle emissions are actually based on the total GHG emissions from the MOVES model divided by fuel use, which results in the same values as fuel carbon plus a vehicle CH_4 and N_2O factor.

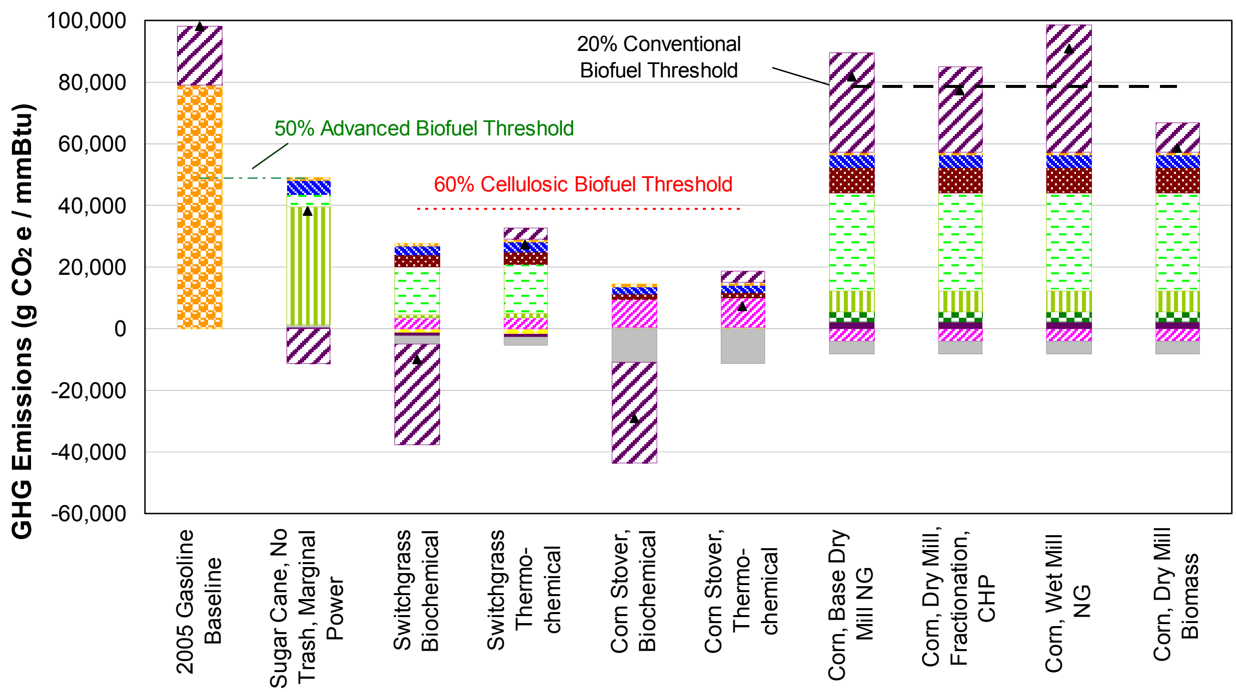

Figure 5.5. EPA RFS2 Results, fuels compared to gasoline (see legend below)

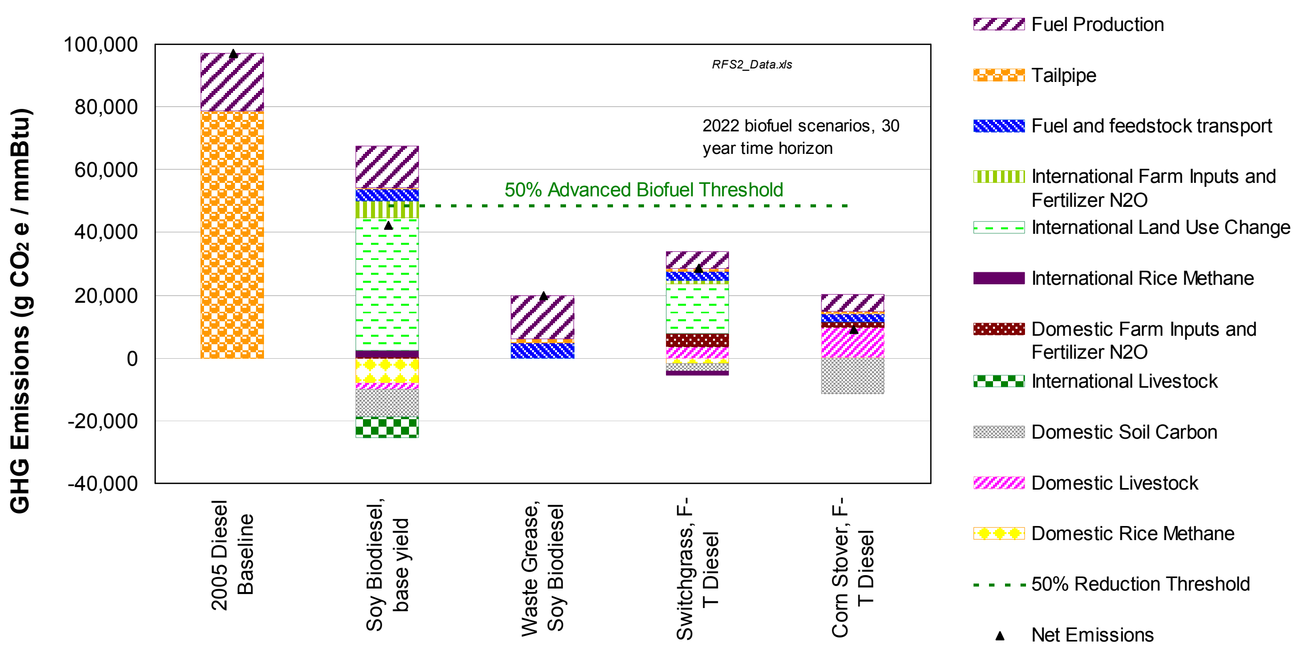

Figure 5.6. EPA RFS2 Result Projection for fuels compared to diesel

5.5.3. European Studies

JEC (2008) presents a European analysis of iLUC studies and several studies are performing 'meta-analyses' of models and approaches to iLUC including RFA (E4Tech 2010) in the UK and IFEU in Germany. The JEC commissioned a comparative analysis on iLUC models (not yet publicly available). Life Cycle Associates was involved in a GTAP analysis for this study. The

Renewable Fuels Agency in the UK (RFA UK) commissioned two studies on iLUC effects for biofuels sold through the RTFO in the UK (RFA UK 2010). E4Tech is working on an iLUC modeling approach and the RFA UK published a joint study between consultancies Winrock and Ecofys (RFA UK 2009).

The E4Tech Casual-Descriptive Model focuses on a combined process of evaluating direct and indirect systems with particular attention to co-products use and feedstock use/effects for other sectors. The approach includes a three-step approach to assess the magnitude of the iLUC effects at each stage of the consequential analysis:

1. Statistical analysis of historical trends in econometric data will be used to quantify the market-induced impacts of iLUC.
2. Economic analysis (e.g., projections of the marginal cost of producing crops in different countries, if available) will be used to understand the extent to which it supports the trends projected through extrapolation of historic trends.
3. Expert input and literature review will provide qualitative validation of the results of the statistical analysis.

5.5.4. Comparison of Econometric Model Results

Since the Searchinger and Heimlich (2008) analysis, several analyses have addressed the key differences in iLUC results and possible directions for further work. Figure 5.7 shows that more recent corn ethanol estimates for iLUC are between the 21 to 30 g CO_2 e/MJ. The most recent corn ethanol iLUC study (Tyner 2010) is under evaluation by ARB. This study includes parameters that have been lacking in other studies, mainly adjustment of yield increases; it estimates a much lower land area: an average 0.12 hectares of land needed to produce 1,000 gallons of corn ethanol with an iLUC factor of 14 g CO_2 e/MJ. In a recent analysis, including uncertainty in GHG estimation using an earlier version of GTAP-BIO, Hertel, et al. (2010) concluded that the corn ethanol-induced emissions from land use change range between 2 and 51 g/MJ.

Some of the differences between the GTAP and FAPRI approaches to determining LUC are discussed in Section 5.4. The models predict different amounts of land conversion per unit of crop produced in different parts of the world, in part because of the structure of the models. For example, GTAP predicts a greater land conversion in Canada because it considers trade constraints among countries. Figure 5.8 summarizes results from GTAP and FAPRI.

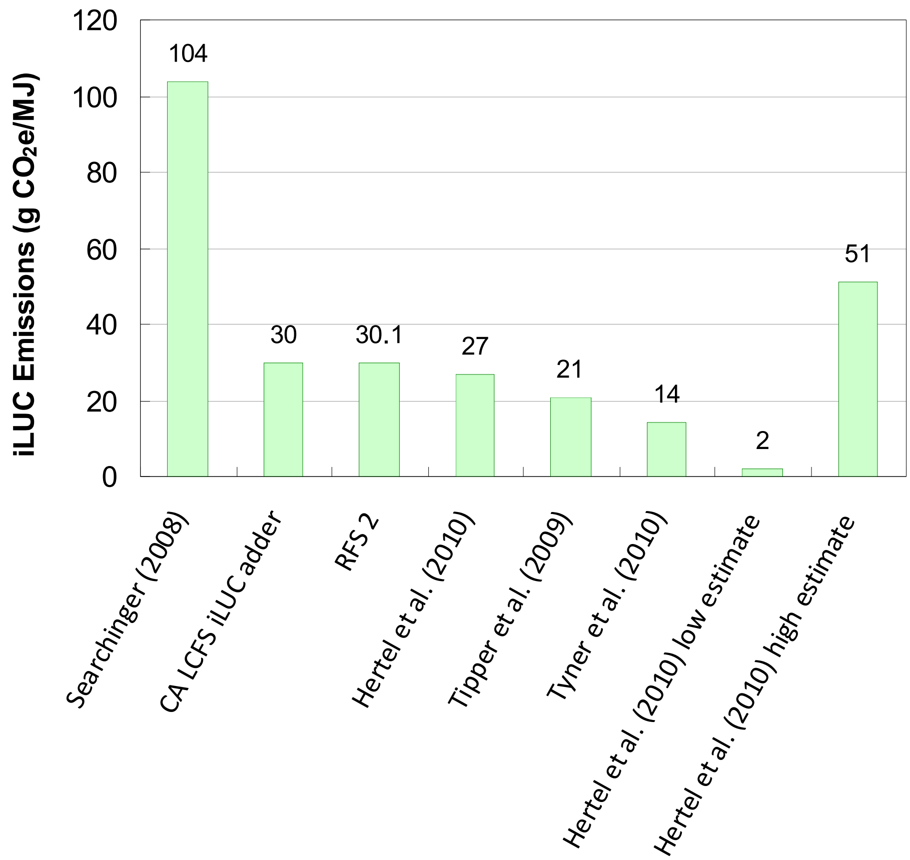

Figure 5.7. Estimated Indirect iLUC from Corn Ethanol from Various Studies or Initiatives

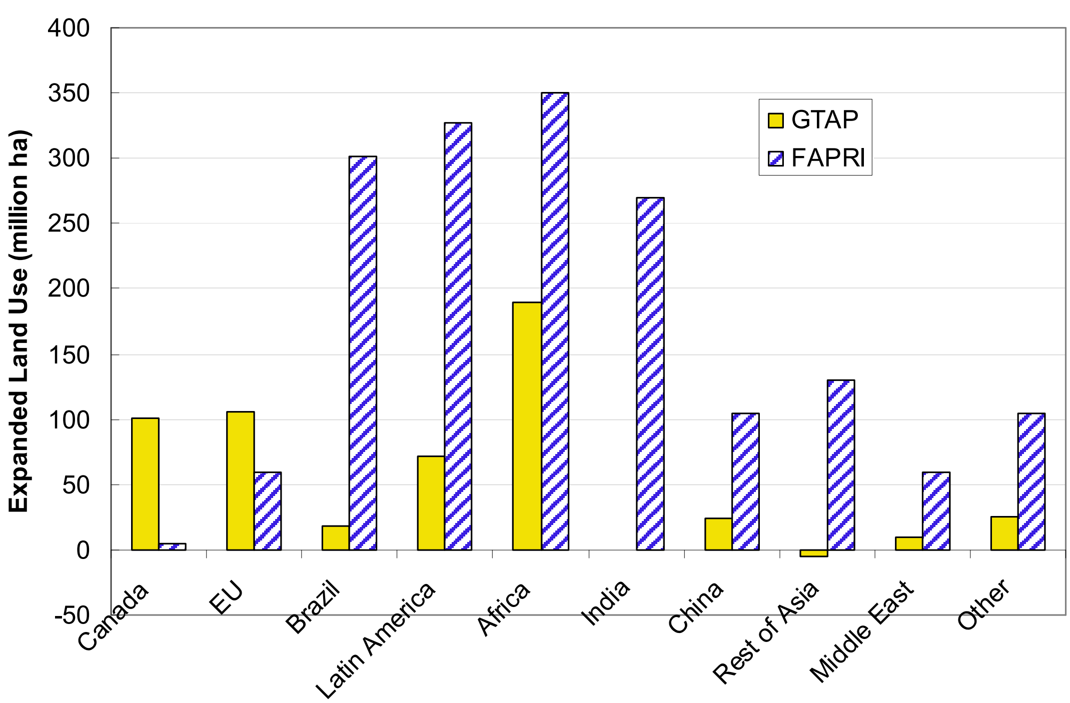

Figure 5.8. Comparison of Land Conversion from GTAP and FAPRI Predictions

Table 5.4 compares the changes in land cover predicted for corn ethanol for the RFS2 analysis and ARB's GTAP analysis for the LCFS. The predictions show significant difference in predicted land cover change. The differences are largely due to assumptions about yield and yield expansion with increase in crop production. Recent GTAP analyses from Purdue predict lower levels of land cover than prior GTAP runs because the model analyzes the availability of pasture land and shifts from pasture to crop production.

Table 5.4. Changes in Land Cover from EPA RFS2 and GTAP

	Agro-economic Models			US. Corn Acreage	
Parameter	EPA RFS2 2010	GTAP, ARB LCFS	GTAP, Tyner 2010		
Scenario	2022	2001 GTAP Database		2005 Data	2020 GREET Projection
Ethanol (bgy)	13 to 15	1.8 to 15	1.8 to 15		
Cropland (M ha)	1.8	3.8	1.9	10.1	
Land Use (m^2/ L)	2.0	0.7	0.4	6.7	5.5
Land Use (kha/M ton)	253	92	50	843	702

Several inputs affect the land cover changes predicted by agro-economic models. The models predict the change in displaced crops, thus the yield of all the affected crops determines the required land to produce biofuel feedstock. As indicated in Table 5.4, the incremental land cover predicted by agro-economic models is lower than that of the average or projected average corn yield. The amount of land required for biofuel production is often predicted as much less than the average land requirement to produce biofuel feedstock. The cause of the land cover change is associated with several factors, including:

- Displaced crop
  - For example, Brazilian soy beans have higher yields than U.S. grown soybeans grown on corn land. (Biofuel production could also expand onto land with worse yields, resulting in an increased requirement for land.)
- Shifts in commodity usage
  - For example, as additional corn use stimulates higher prices, the sales of beef drop and other meat products can increase. An offsetting factor would be the sales of DGS from corn ethanol make beef feed less expensive.
- Induced yield
  - Yield of crops are predicted to increase as prices rise, stimulated by higher profits per hectare.
- Food/feed price rationing
  - As prices increase, consumption drops. Thus, less global crop output is required to make up for crops used for biofuel production.
- Consumer price response
  - For example, ethanol provides additional fuel on the market, so gasoline prices drop slightly and consumers drive more. This response is a variant of the rebound effect.

Projected yields are a key input because of the following relationship that determines the converted area from new land associated with an incremental change in feedstock. Incremental crops can be produced by improving yield or expanding land. The following relationship shows the importance of the "price induced yield" effect in determining incremental land area.

$Q = Ay$

Where Q = crop volume, A = area, y = yield. δy refers to change in yield.

$\delta Q = (A\delta y)_{existing} + (y\delta A)_{new}$

Only the right side term results in new land converted to biofuel production. These effects are both taken into account in FAPRI and GTAP.

5.5.5. LUC Modeling Issues

The modeling of LUC associated with biofuels is a new field that addresses an uncertain topic. The following issues could be addressed to improve the LUC analysis for biofuel applications.

Metrics, Inputs, Output

Numerous assumptions, inputs, and endogenous calculations provide the basis for calculations of LUC impacts. The various LUC models should provide both the inputs and endogenous parameters on a consistent basis, including:

Inputs:

- Biofuel volume[37]
- Fuel logistic constraints (blend wall, etc.)
- Yield response elasticity and predicted crop yield
- Biorefinery yield and predicted changes in yield
- Fertilizer application requirement and projected changes
- GHG emission factors (either internal or external to model)

Results:

- Land cover change by region or land type and crop
- Attribution of changes in land cover including crop demand, co-products, yield response, consumer price response to fuel, food response to price

Econometric Data, Biorefinery Operation

Agro-economic models use econometric data (economic output by industry group) to represent the components of a food production or biorefinery activity. This treatment is consistent with the way the economic models work, but causes significant challenges in the flexibility of using such models, because many key parameters are locked into economic sectors. For example, the ethanol sector in GTAP includes all of the direct inputs to ethanol production such as corn, natural gas, electric power, and chemicals as well as indirect inputs. The relationship between the corn ethanol industry and actual ethanol plant parameters and econometric data is difficult to document and maintain consistent with biofuel scenarios. A typical scenario for marginal ethanol

[37] See Section 4 regarding comment of fuel properties. A 1% error in the heating value of fuel translates throughout the LUC calculation.

production would include a mix of natural gas and biomass fired plants[38]. The mix of plant technologies may change for different purposes of running the model, but the resource mix is hard-coded into the economic sector for ethanol. Therefore, if model runs were to consider plants with different levels of process heat, power consumption (cogeneration), or other operational parameters, the ethanol sector would no longer represent these technologies accurately.

No easy solution to this problem is available because econometric models act on sectoral representations of industries, and converting biorefinery data to econometric data is labor intensive. A new economic sector is developed to represent each fuel technology. Other economic studies using partial equilibrium models have met this challenge by disaggregating the components of the fuel industry to allow for flexibility in assessing the impacts (RCF)[39].

A more transparent relationship between econometric data and LCA parameters should be documented and used to test the sensitivity of economic inputs to iLUC and other indirect effect calculations. The challenge becomes apparent for new technologies where the projections for biorefinery performance can differ significantly with respect to yield, co-product feed, chemicals, and electric power use or export.

<u>Bundled LUC, Products, Co-products, High Protein DGS, Sorghum, and Butanol,</u>

The current systems for iLUC analysis could improve the reporting and validation of intermediates such as LUC associated with feedstock, co-products, fertilizer use, and other process inputs. Agro-economic models tend to bundle many key parameters, making the intermediate values difficult to inspect and use for off-model calculations.

Ideally, LUC results could be presented per unit of feedstock and co-product. This representation would allow for the calculation of other fuel pathways without the need to develop a rigid equilibrium model structure. A disaggregated analysis would allow for calculation of other biofuel pathways or variants on fuel pathways not considered by the EPA or ARB. For example, knowing the LUC per bu of corn and DGS, the LUC effect for different biofuel options should be calculated. These might include ethanol plants that burn DGS for process heat or butanol plants that use corn as a feedstock and produce DGS as a co-product. Agro-economic model results could also be used to develop reduced form models that allow for the more flexible calculations and sensitivity analysis.

The bundling of model scenarios also results in an important effect on LUC analysis. For example, sorghum can be grown on corn land; so the iLUC associated with sorghum might be expected to be the same as that for corn ethanol (per hectare of land used for crop production, not per gallon of fuel produced), with an adjustment for the relative amounts of feed produced from each crop (Tyner 2010). However, if sorghum is treated as a separate crop system, the iLUC results will likely be different. Thus, the choice of aggregation affects the modeling outcome. A similar paradox might occur with corn butanol. Here the same crop can provide the feedstock for a different fuel. Should the iLUC results per hectare of land be the same?[40]

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[38] The GTAP econometric data for ethanol includes no coal because it represents new plant production.
[39] The RCF study on the hydrogen economy and employment developed separate economic sectors for components of the hydrogen economy to allow for the summation of components for different scenarios with different mixes of production and delivery technology.
[40] After adjusting for the relative quantities of co-products.

Finally, the treatment of co-products in LUC analysis needs to be transparent to compare consistency within the WTW calculations. FASOM solves this problem by addressing fertilizer use, co-products, electric power consumption, and their consequential effects. However, this treatment comes at a loss of transparency.

Yield Improvement

Projected yield improvements can result in a significant reduction in required land area. The basis for the yield improvement is econometric studies that relate agricultural activity to prices or economic activity.

GTAP predicts the effect of cropland expansion based on the demand for a particular crop whose production increases, combined with the yield of the crops at the frontier of cultivation. GTAP for example projects modest contributions from increased yields, but part of the price-induced yield increase is countered by the effect of the considerably lower yield assumed in GTAP for the crop produced on new area. Ideally, the yield projections from agro-economic models could be compared to projections based on agricultural improvements, fertilizer and technology projections.

Economic studies attempt to determine yield response from historical data (Lynwood 2009). Unfortunately, the correlation of yields to price alone provides opportunities for autocorrelation even with sophisticated efforts to manage the data (Berry 2009). More research is needed on a price yield response that relates data independent of price with yield and price/yield response as well as bottom-up models that predict price/yield based on the economics of agricultural inputs.

Pasture

A key factor in LUC models is the role of pasture or grazing land. If pasture land is used more effectively with higher rates of cattle stocking, then this land could be available for biofuel production. Modifications to GTAP include efforts to estimate the productivity of marginal land. The TEM database is used to estimate the net primary productivity of agricultural land as a proxy for crop productivity. Predictions of cattle stock remain challenging as the response of cattle stocking to agricultural activity requires further research.

Historical Trade Patterns

An important feature of agro-economic models is that they examine the interrelationship between crops and their trade elasticities. These relationships are based on historical data and enable the models to predict what feedstocks will be produced globally. GTAP also takes into account trade history and trade barriers among countries.

The effect of these elasticities requires careful examination as they have a significant effect on the LUC analysis for some feedstocks. The uncertainty is significant in the oilseeds area where trade in oils and meal varies from year to year and is affected by parameters such as carryover stocks, customer preference, and trends in the vegetable oil market.

Other factors cause model results to diverge for similar scenarios where production is shifted from countries with high yields to relatively less developed countries with lower yields. GTAP, which uses Armington elasticities that base trade behavior on prior history, could concentrate crop production too much on the developed world (for biofuel production in the developed world), where yields are higher and thereby under predict land conversion (Edwards 2010).

Biofuel Demand, End Use, Oil Price, Rebound

LUC models include various levels of integration with petroleum energy systems. Some of these interactions include:

- Effect on gasoline prices
- Effect of blend wall on need for E85 sales
- Interaction between other biofuels
- Effect on petroleum price

Economic-based LUC models estimate these effects to varying degrees, and the impacts of general economic effects are commingled with iLUC effects. However, other indirect effects (such as fertilizer resource depletion) are not examined in LUC models. Therefore, the selective analysis of indirect issues other than LUC is an issue.

Choice of Baseline, Timeframe, and Projections

The choice of time horizon, technology projections, and economic model parameters affects LUC analysis through many mechanisms. For example, the EPA's analysis for 2022 includes a mix of biorefinery yields, economic parameters, and crop and fertilizer yield projections. The 2022 time horizon is the focus of the EPA's analysis because it represents the full implementation of the RFS2.

5.6. Carbon Stock Data

5.6.1. Carbon Cycle

The terrestrial biosphere can act as both a source and a sink for carbon. The carbon cycle is the mass transfer of carbon by natural geological, physical, biological, and chemical processes (Grace 2004) between the biosphere, hydrosphere, and the atmosphere. Biogenic greenhouse gas (GHG) fluxes associated with agriculture include the storage of atmospheric carbon in plant biomass due to photosynthesis, respiration, decomposition, and the uptake or release of carbon into roots, soil, or back to the atmosphere. Non-CO_2 emissions (CH_4, N_2O) from agricultural practices vary depending on the management practice employed. The atmospheric uptake of carbon dioxide into plant material is considered a credit against the biogenic carbon in the fuel. However, the biogenic components of feedstock production and land use are important elements of a biofuels' life cycle impact, and these emissions should include changes in soil carbon and aboveground flora and belowground soil and biomass.

Land conversion, such as converting forest to pasture, results in the removal of variable quantities of above-ground biomass, depending on the forest structure and type. However, such land conversion causes a smaller change in soil carbon. (Brown and Masera 2003). Conversion of forest to cropland also releases large quantities of soil carbon. However, reduced tillage practice or crop residues re-incorporated back into the agricultural system can lessen this effect and provide the benefit of improvement of soil quality (Fargione, et al. 2008, Kim and Dale 2009; Post and Kwan 2000). In addition, if existing cropland is tilled much (over 25%) of the soil carbon is released over time (Delucchia 2009). No-till practices can help to build up soil carbon (Houghton and Hackler 2006) and perennial crops will add to soil carbon mass in variable quantity and over time. The effect of tillage practice remains uncertain (Cruse 2009, Wilhelm 2007).

Carbon Cycle Effects
Altered by: ⚒ Direct land use conversion to crops ⚒ Improved by some practices ⚒ Increased demand causing indirect conversion of land elsewhere ⚒ Harvested Wood Potential ⚒ Emissions variable and questions remain: methane, roots, perennial systems

Converting cropland or CRP land to pasture or forest generally results in increased storage of carbon (Guo and Gifford 2002, Houghton 2003, Liska and Perrin 2009, Gibbs, et al. 2007). Spatial and temporal relationships between agricultural patterns and practices and the net amount of carbon stored has not, to date, been adequately quantified.

Direct land use change can be defined as the type of activity being carried out on a unit of land (Gnansounou, et al. 2008) and IPCC updated guidelines for Land-use, Land-use Change and Forestry (IPCC 2003). These guidelines have set default values for these above-ground land use changes. These land categories are a mixture of land cover (the type of vegetation covering the earth's surface) and land-use classes (IPCC 2003). Six top-level land categories for greenhouse gas (GHG) inventory reporting are specified. These categories include forest land, cropland, grassland, wetlands, settlements, and other land.

IPCC estimates that ~1.5 billion tonnes of carbon are emitted to the atmosphere each year from forest and grassland clearing, which accounts for 20% of annual CO_2 emissions (IPCC 2000 and 2006a reports on Land Use and Land Use Change[41]).

5.6.2. Soil Organic Carbon (SOC)

Global soil organic carbon (SOC) estimates are 2,300 Pg C as shown in Figure 5.9. This is three times the estimated 760 Pg in the atmosphere. Yet this soil organic carbon sink is also one of the major sources of atmospheric CO_2, as also shown in Figure 5.9. Soil naturally acts as a carbon sink, the magnitude of which is affected by a combination of factors such as soil moisture, pH, salinity, texture, and the presence of microbes and plants that live in and above the earth. Natural and anthropogenic external factors such as seasonal change, tillage, and fertilizer and water inputs also have a strong effect on the CO_2 cycle.

[41]Or use the Global Carbon Project data: the growth rate of emissions continued to speed up, bringing the atmospheric CO_2 concentration to 383 parts per million (ppm) in 2007.

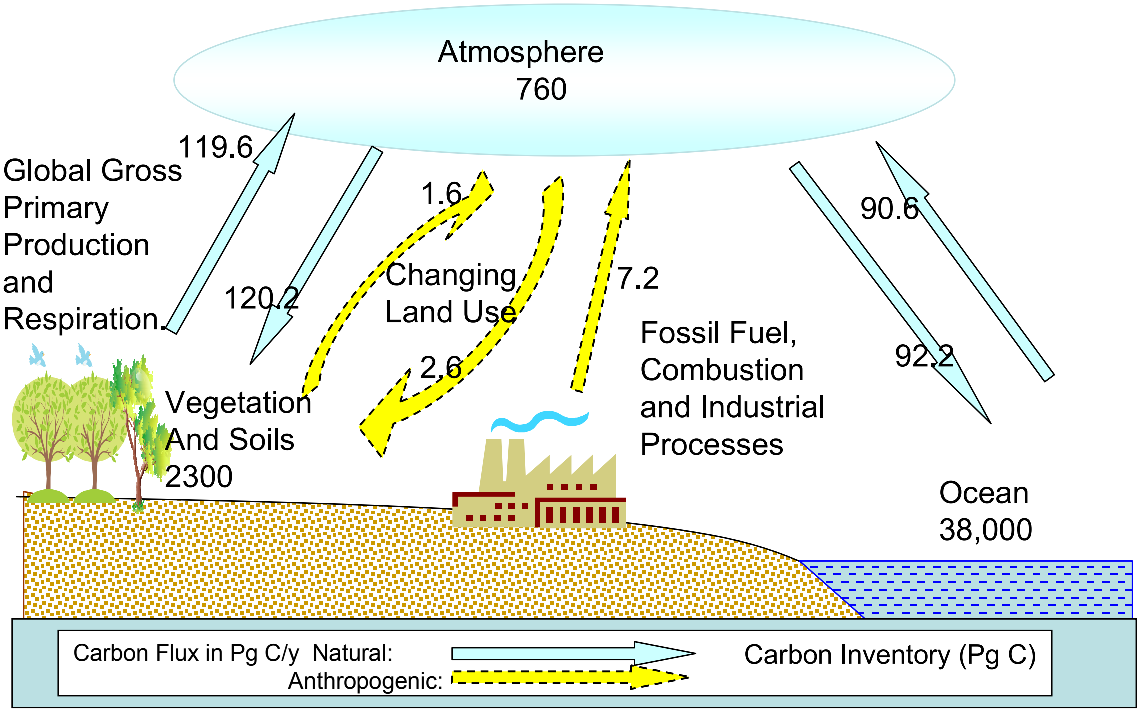

Figure 5.9. The Global Carbon Cycle (Adopted from IPCC 2001, 2007)

SOC mapping is highly variable in terms of total carbon estimates stored in vegetation vs. in the soil and root systems. The highest stores are found in the boreal and tropical regions as illustrated in Figure 5.10. Peat lands are especially high in soil carbon in the boreal areas, and yet often lumped together in estimates from tropical peat land areas as 'forest', for example (Harris, 2009).

5.6.3. Carbon Stock Evaluation Methods

Typically, root biomass is estimated as 20% of the aboveground carbon stocks in other pools (Houghton 1999, Archard, et al. 2006), based on literature research. Similarly, carbon stocks including dead wood (felled trees, leaves, branches, etc.) are generally assumed to be approximated at ~10-20% of the aboveground forest carbon for primary forests (Houghton and Hackler 2006). Soil carbon stocks are largest in peat lands such as found in Southeast Asian peat swamps.

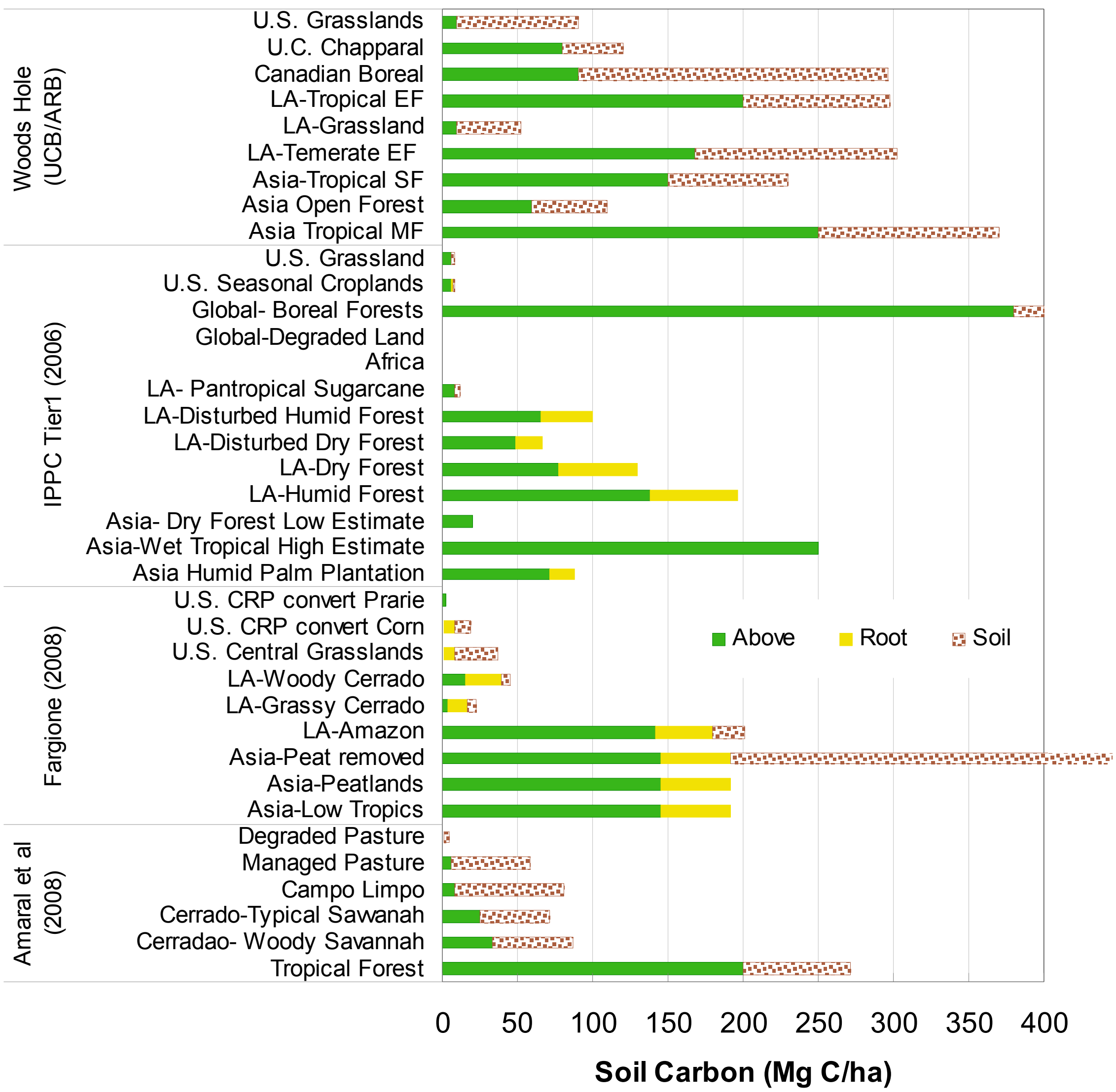

Figure 5.10. Comparison of Above vs. Belowground Soil Carbon Based on Winrock/REDD/IPCC Methods

The tropics are estimated to contain 340 billion tonnes of carbon (Gibbs, et al. 2007), which equals more than 40 times the anthropogenic emissions from fossil fuel use (Canadell, et al. 2007). However, the flux and transport through the forest system of this carbon varies considerably compared to a grassland ecosystem. Estimates of carbon and the sequestration potential of a system are also variable and are topics of debate because estimates include heterogeneity between interpretations of the same datasets. Coarse resolution optical data (<1 km) is optimal for general distribution of forest types but cannot estimate change[42]. Multiple sets over multiple years of more finely-tuned spatial data (MODIS, Landstat, etc.) have addressed

[42] Much finer satellite imagery is used in other applications.

this problem with some success. Still, the IPCC default values for various land use factor types are variable and depend on the management practice, level of land use (time), and temperature and moisture regimes as shown in Table 5.5.

Table 5.5. Relative Stock Change Factors (over 20 years) for Different Management Activities on Cropland[43]

Level	Temperate regime	Moisture regime	IPCC defaults[a]	Estimated Error (+/-)	Description
Long term cultivated	Temperate/ Boreal	Dry	0.8	9%	Represents area continuously managed for >20 yrs, to predominately annual crops. Input and tillage factors are also applied to est. C stock changes. LU factor estimated relative to use of full tillage and nominal ('medium') carbon input levels.
		Moist	0.69	12%	
	Tropical	Dry	0.58	61%	
		Moist/Wet	0.48	46%	
	Tropical Montane	n/a	0.64	50%	
Paddy Rice	All	Dry and Moist/Wet	1.1	50%	Long term (>20 year) annual cropping of wetlands. Can include double-cropping with non-flooded crops. Tillage and input factors not used for paddy rice.
Perennial/ Tree	All	Dry and Moist/Wet	1	50%	Long term perennial tree crops such as fruit and nut trees, coffee and cacao.

[a] Stock change factor × carbon stock = GHG emissions. Note stock change factor for Paddy rice is > 1, which includes both CO_2 and CH_4 emissions.

A variety of methods are employed in different analyses of global soil carbon stocks (Searchinger and Heimlich 2008, Brown and Masera 2003, Houghton 2003, 1999). These estimates are based on analyses that are extrapolated from either original data on carbon estimates or regional samples derived from estimating the annual flux of carbon between terrestrial ecosystems and the atmosphere. IPCC methodology for carbon calculation is often employed to develop emission factors for various ecosystems throughout the world (IPCC 2006b).

The above-mentioned methods are not always straightforward because some carbon stock estimates are compared with historical datasets added or combined with new ground data with spatial data averages. For example, Houghton's dataset (Houghton 1999), used later by Woods

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[43] IPCC Good Practice Guidance:

$\Delta C_{LOMineral} = [(SOC_0 - SOC_{(0-T)}) \times A] / T$ $SOC = SOC_{REF} \times F_{LU} \times F_{MG} \times F_I$

where F_{LU} = stock change factor for land use or land-use change type; F_{MG} = stock change factor for management regime, and F_I = stock change factor for input of organic matter; all factors are dimensionless and this equation represents land converted to 'other land'

Hole (2000) and MIT, was based on 1m core samples from original data from Schlesinger, et al. (1973 and 1981). Houghton revised his dataset in the 2003 Tellus report on values up to 2000 (Houghton 2003). His data are extrapolated from 1875-2000 net flux of carbon cycling. IPCC (Winrock 2009) "default" values are provided only for three land conversion types - from forest, grassland, or croplands into biofuel production.

The IPCC Tier 1 approach only accounts for CO_2 emissions. The default value for burning (0.9) assigns the remaining 0.1 to unburned material that is stored long term. Tier 1 assumes that post conversion all carbon stock is converted in year one either on or off-site via decay processes. Tier 2 methods used by Winrock, for example, apply some regional/country specificity to above or belowground carbon and are used in combination with IPCC default values. Also the C loss can be attributed to 'other processes' like burning or harvesting (not just decay as in Tier 1). Non- CO_2 emissions, such as the various species within the N cycle, can be included as a non-default value where data are available. Another feature of Tier 2 methods applies the accounting of carbon in wood products. IPCC methods treat the wood as fully oxidized for inventory accounting, while in LCA accounting the wood products are treated as stored.

IPCC Methodology

What Does it Mean for iLUC?

- Tier 1 is least accurate: default values only.
- Tier 1 estimates do not include CH_4 and N_2O from burning while Tier 2 estimates by Winrock are broad generalizations.
- Tier 3 is 'best', includes regional data. However, global sampling efforts are slowly underway and in the developing world expensive and difficult.
- Forest systems most difficult to analyze- spatially and temporally.

For aboveground analysis, spatial data are used, and the analysis relies on interpretation of datasets where resolution and availability are the two most important criteria for evaluating data, but still cannot interpret change unless several datasets are combined with historical trend data (Gibbs, et al. 2007). Forest cover is likely the most difficult to estimate and even with advances in remote sensing equipment and analysis, there is still relatively low confidence in using these data to estimate forest cover in some regions. Forest categories are particularly difficult to estimate from fallow to reforested areas (Sader, et al. 1989). This point identifies one of the critical issues in LUC- linking an event to an effect.

Further work on improvements to sensory data is evolving to include crop type classification for certain countries or regions is possible using MODIS data and observations from other instruments (e.g., Landsat Enhanced Thematic Mapper (ETM+), SPOT, and Advanced Wide Field Sensor (AWiFS).

5.6.4. Comparison of Carbon Stock Analyses

As Figure 5.10 depicts, LUC studies vary in their calculations of above and belowground carbon, shown in the figure by forest type. For example, the forests in the Americas are highly variable themselves but are often used for biofuel LUC studies because they contain the types of forests biofuels depend on; specifically from dry cerrado in Brazil (for sugarcane ethanol) to U.S. croplands in the Midwest (for corn ethanol) to tropical regions (for possible palm for biodiesel).

The IPCC provides biome averages of carbon stocks for various regions of the world and Winrock developed the methodology to ascertain carbon stocks for IPCC. Gibbs, et al. (2007)

describes the Tier 1 approach used by IPCC (where these averages are used) and compares IPCC values to regional level carbon stock estimates from various studies (Goetz, et. al, 2008, Houghton 2003, De Fries, et al. 2002, Brown, et al. 1989, Archard, et al. 2006) and then a total range of each dataset compared to IPCC. The results in Figure 5.10 show variance but also provide ranges for forest carbon stocks.

The IPCC Tier 2 method employs some regional data (or 'all' regional for Tier 3) for above or belowground stocks in combination with IPCC default values. Core samples for SOC follow IPCC to 30 cm deep, and for spatial cover, satellite data is used to the highest resolution possible (preferably 500x500 m). Carbon loss can be attributed to 'other processes' like burning or harvesting (not just decay as in Tier 1), so non- CO_2 emissions come into play as the N cycle can be included as a non-default value where data is available. Therefore, the Tier 2 to 3 methods are best if a regional analysis aims to count carbon in wood products as fully oxidized in the year of removal.

Quantifying gross forest cover loss (GFCL) represents only one component of net change, and the processes driving GFCL and rates of recovery from GFCL differ regionally. For example, the majority of estimated GFCL for the boreal biome is due to a naturally induced fire dynamic (Hansen, et al. 2010).

Figure 5.10 also identifies the requirement to identify data inputs and methods due to variable results. For example, if roots are not calculated or peat emissions are omitted, the carbon stock values are substantially lower than if they were included.

The type of crop also affects the effect on carbon stocks. Most analysis is based on the conversion of land to row crops such as corn and soybeans. Perennials such as sugarcane, Miscanthus, and oil palm build up root mass and store carbon. Another factor affecting soil carbon is strategies such as biochar that would lead to a build up of carbon in the soil (Roberts, et al. 2010).

5.6.5. Model Inputs for Soil Carbon Release

Studies of land conversion typically assume that 25% of the carbon in the soil reacts to produce CO_2 over time, on average (Houghton and Hackler 2006). The Searchinger, et al. study applies this loss factor to all ecosystem types. However, the percent carbon lost varies across and within ecosystem types depending on climate, precipitation, type of forest, and other factors as shown in Figure 5.11. An alternative study presents a loss of 40% of soil carbon in the conversion of forest to cropland, based on a 2002 meta-analysis by Guo and Gifford (2002). The Guo and Gifford study (2002) indicates that approximately 55-65% of soil carbon is lost when grassland is converted to row crops, as also shown in Figure 5.11.

The IPCC includes a tool for estimation of changes in soil carbon stocks associated with management changes in croplands and grazing lands based on IPCC default data. For the remaining land use types, the tier methodology is employed in various ways and depends on the availability of data disaggregated by region, type, or climate zone. For example, the general calculation for annual changes in carbon stocks (tonnes C/year) within grassland, is:

$\Delta C_{GG} = \Delta C_{GGLB} + \Delta C_{GGSoils}$
ΔC_{GG} = change in grassland remaining grassland

ΔC_{GGLB} = change in living biomass in grassland remaining grassland
$\Delta C_{GGSoils}$ = change in soils in grassland remaining grassland

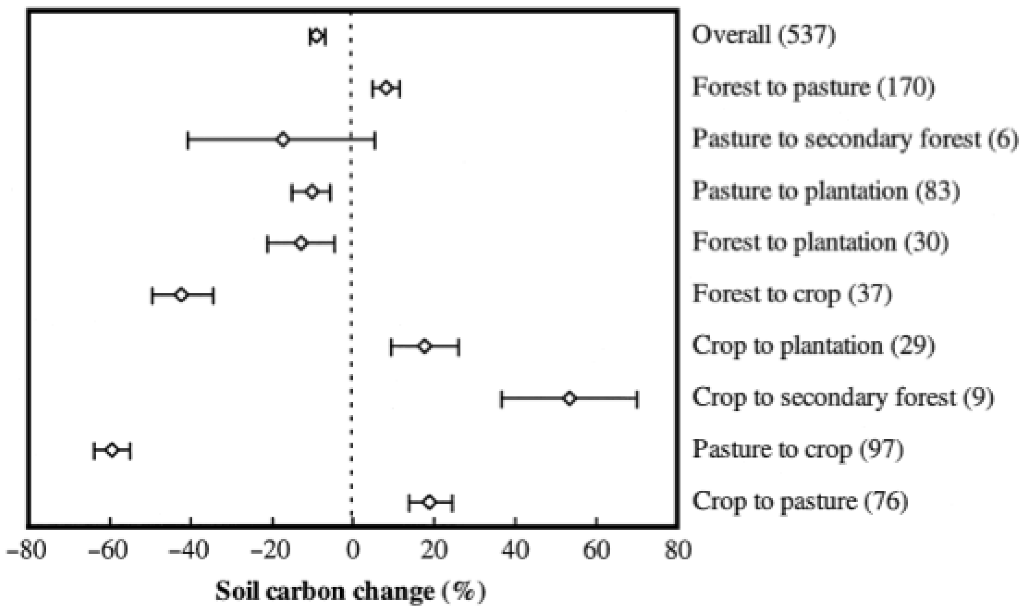

Figure 5.11. Soil Carbon Response to Various Land Changes (95% Confidence Interval and Number of Observations Shown). Source: Guo and Gifford, 2002

5.6.6. Roots, Rhizomes, Perennials

While direct estimates of belowground biomass stocks are possible, carbon stocks are typically approximated using expansion factors applied to aboveground biomass stocks. Such expansion factors are called root to shoot (R) ratios of belowground to aboveground biomass. These ratios may vary by grassland type, climate region, and management activity. The equation below demonstrates how to estimate total (above and belowground) biomass stocks. Note that aboveground biomass (B_{AG}) must be estimated first and then applied in the equation. Total biomass stock (B_{Total}), belowground biomass stock (B_{BG}), or aboveground biomass stock (B_{AG}) from equations above are needed to estimate changes in biomass stocks over time.

$B_{Total} = B_{AG} + B_{BG}$, and
$B_{BG} = B_{AG} \times R$

Where:

B_{Total} = total biomass, including above- and belowground, tonnes dry mass
B_{AG} = aboveground biomass, tonnes dry mass
B_{BG} = belowground biomass, tonnes dry mass
R = root-to-shoot ratio, dimensionless

For grassland systems, the underground carbon share is far more substantial than the aboveground carbon because systems of perennial roots can be extensive. For example, European *Miscanthus sp*. trials estimate 10–20 tonne dry matter ha^{-1} for the perennial rhizomatous root system (Hanson, et al. 2003). More detail is available with Tier 3 inventory systems, which are not used in current LUC models.

5.6.7. Methanogenic Activity

When a forest is cleared for agriculture (e.g., pasture or annual cropping), termite abundance, biomass and species richness is generally reduced (Bignell & Eggleton, 2000), especially if there is burning involved. However, there may be cases after forest disturbance where there is a greater amount of nutrients from the cut vegetation (especially if left on the surface of the soil) made available to the termites in neighboring ecosystems (e.g., savanna) leading to a colonization of other species after forest species have been removed, effects of which will only be seen in the years following the forest disturbance.

The current view is that the greater part of the gas produced by termites is oxidized locally (in the soil and walls of the nests). This finding is consistent with that of other groups (e.g., Japanese) working independently. Professor David Bignell (Queen Mary, University of London) and colleagues estimate that gross production of methane by termites is about 4 to 5% of global totals. Only about 30% of this reaches the atmosphere aboveground, possibly less. No one has investigated whether methane produced in tropical forests (at ground level) exchanges with the air above the canopy. There are wide differences across biomes and land uses. Forests should have greater gross production than savannas, but methane oxidation in both settings is reduced by disturbances to the soil (logging, tillage, desertification, etc.) (Bignell, personal communication.)

Methanogenic activity and subsequent microbial, fungal, and organisms should be examined further for appropriate use in LUC calculations.

5.6.8. Comparison of Woods Hole and Winrock Carbon Stock Data

Several studies identify a series of combined approaches to measure carbon flux to present an LUC effect (Dixon, et al. 1994, Guo & Gifford 2002, Houghton, et al. 2003, Searchinger and Heimlich 2008, Brown and Masera 2003, Lapola, et al. 2010). Woods Hole data, used by Searchinger and ARB, is primarily based on analyses that are extrapolated from either original data on carbon estimates or based on the annual flux of carbon between terrestrial ecosystems and the atmosphere. For example, Houghton's dataset (used later by Woods Hole, MIT), was based on 1 m core samples from original data from Schlesinger et al. (1973 and 1981). From here, these analyses have been extrapolated, either with historical datasets added or combined with new ground data with spatial data averages. It should be noted that Houghton revised his 2000 dataset in the 2003 Tellus report on values through to 2000. His data is extrapolated from 1875-2000 net flux of carbon cycling.

Woods Hole data uses IPCC default values, which are provided only for three land conversion types -- from forest, grassland, or croplands into biofuel production. The analysis applied IPCC Tier 1 factors. Woods Hole estimated carbon pools using data that does not reflect actual regional share, such as lumping Brazil under the Latin American figures. Another study estimates the different types of Brazilian forest (cerrado separated by typical and woody) rather than Woods Hole that provides overall Latin American tropical forest or wooded forest.

The Woods Hole analysis continues to be used in GTAP results published by Purdue (Tyner 2010). The analyses use somewhat different assumptions than the carbon stock factors used by ARB. Thus, the assumptions on carbon stock factors used in LUC modeling require further analysis. Table 5.6 shows the carbon stock factors used under the EPA's RFS2 an ARB LCFS, which shows the same assumptions for aboveground biomass. GTAP LUC results by country are shown in Figure 5.12.

Differences between Winrock and Woods Hole C Stock Data

- Winrock (ground +regional data); Woods Hole (limited ground data and estimates based on carbon uptake)
- Winrock 30 cm soil depth, Woods Hole 1 m soil depth
- Winrock more land types; Woods Hole few
- Winrock includes forgone sequestration, fire and other effects; Woods Hole does not
- ARB LCFS inputs made adjustments for fire and harvested wood products (in uncertainty analysis)

Table 5.6. Above- and Belowground Carbon Stock Factors for EPA RSF2 and ARB LCFS

Carbon Stock Factors	EPA RFS2	ARB LCFS
Belowground Carbon	IPCC Factors based on soil conditions	25%
Aboveground		
Harvested Wood Products	10% Boreal	10% Boreal
Carbon Conversion	100% of decay	100% of decay
Burning	90%	90%
Decay	100%	100%

The EPA used the Winrock carbon stock emission factors in combination with the land conversion predicted by region from FAPRI. The FAPRI model is used to project location-specific increases in cropland across the world as the result of increased biofuel production in the United States. The next step of the analysis was to decide which land types would be converted to cropland in each of these countries. The EPA based the determination of land use conversion on an analysis of historical land use trends using MODIS satellite imagery from 2001 and 2004. Winrock conducted the satellite imagery change detection analysis and determined which land use types decreased or increased at the country level during this time period.The EPA used this trend to assign land use conversion types to new cropland. Winrock also calculated the GHG emissions resulting from this projected land use change by compiling world-wide data on carbon stocks in different land types.

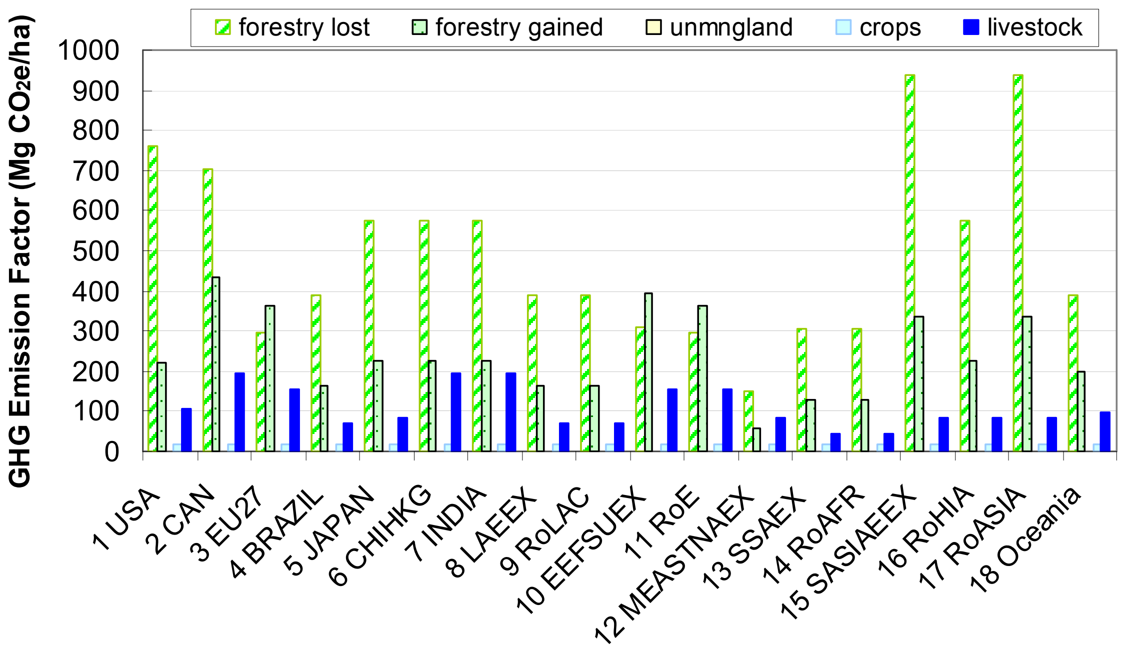

Figure 5.12. Carbon Stock Emissions Factors Used in LCFS for GTAP AEZs.

Although Winrock followed IPCC guidelines (IPCC 2006b) for calculating the change in carbon stocks, resulting from the projected land use changes, and subsequently assigned emissions factors to the five land classes, historical data applied to land use models is critical to ascertain carbon exchanges.

The baseline determination to evaluate change is critical, and the combination of datasets and empirical choices are important issues. Winrock chose the 'top' eight datasets for a global picture on carbon stores, as illustrated in Figure 5.13. Two important parts of this analysis are determining the extent, type, and location of land use conversions occurring due to biofuel production, and developing emissions factors for land conversion. The historical trend chosen by Winrock to estimate the extent of land use change using MODIS imagery changed from the draft rule (2001 and 2004) to a longer period (1998 to 2007) for the final result. Winrock conducted the satellite imagery change detection analysis and determined which land use types decreased or increased at the country level during this time period.

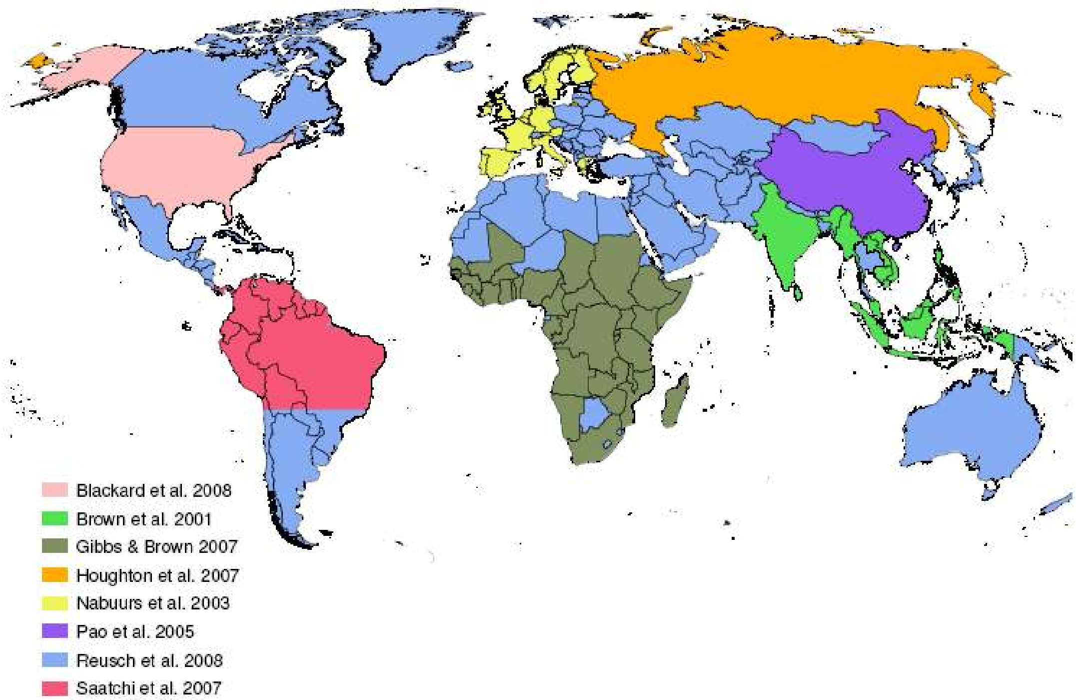

Figure 5.13. Winrock Uses a Combined Dataset from each Region to Analyze Global Carbon Stocks (Source: Winrock 2009)

For the EPA RFS2 analysis, the EPA assumed that these recent drivers of land use change will remain in relative effect and provide the basis for estimating the mix of land cover changes for future biofuel scenarios. Winrock incorporated MODIS satellite data with a refined resolution for the final rule to 500x500 m resolution (refined from the previous 1x1km resolution) and incorporated a longer period, which increased the dataset (from four years previously to eight years currently). Winrock also included reversion rates and forgone sequestration from various land use change events in addition to soil carbon estimates under Tiers 1-2 of the IPCC methodology.[44]

The Winrock results are available in a spreadsheet that enables the lookup of crop conversions for regions in the world (typically at the state of government unit level) for conversion and reversion between the land classes listed in Table 5.7. Figure 5.14 presents the Winrock carbon stock analysis by country.

[44] Winrock actually developed much of the IPCC methodology for measurement of carbon stocks. See: www.winrock.org for publications including two White Papers on iLUC

Table 5.7. Winrock Conversion and Reversion Land Classes

Cnvrsn_1	Cnvrsn_2	Rvrsn_1	Rvrsn_2
Forest	Crop	Crop	Forest
Grass	Grass	Grass	Grass
Savanna	Savanna	Savanna	Savanna
Shrub	Perennial	Perennial	Shrub
Wetland			Wetland
Perennial			Perennial
Mixed			Mixed

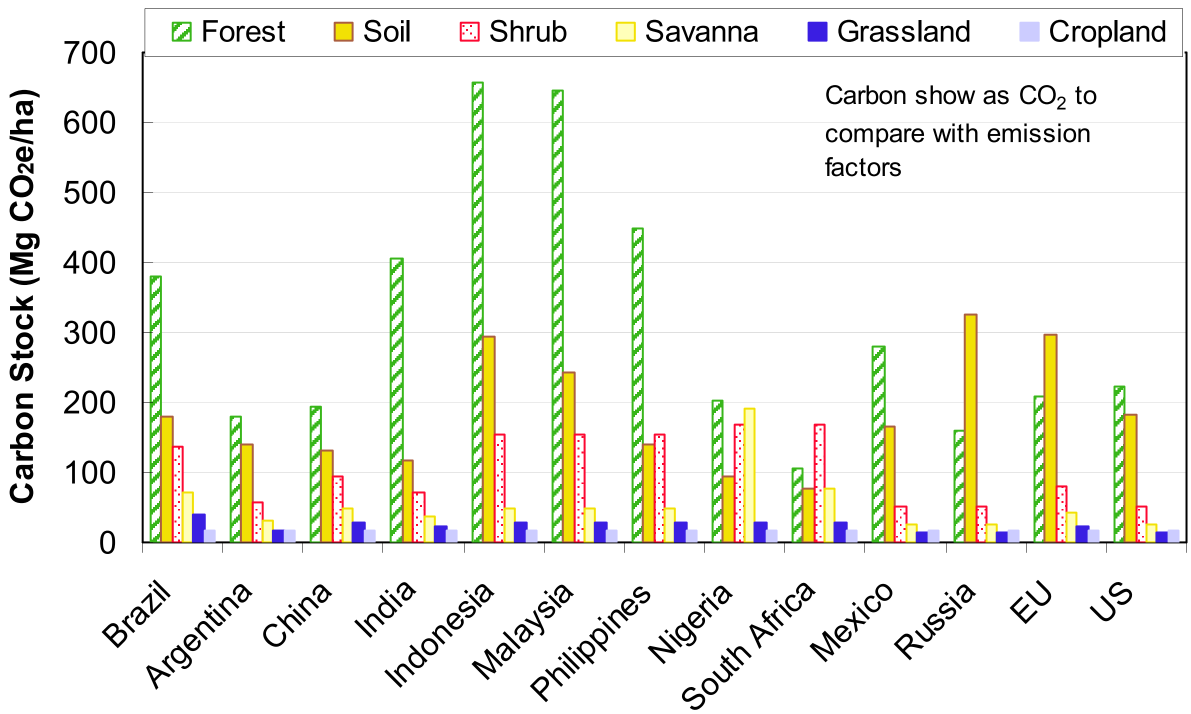

Figure 5.14. Carbon Stock Analysis from Winrock

In general, ground sampling data is lacking in the majority of studies, particularly in forested regions where remote sensing data is of low confidence. IPCC Tier 3 represents data that are produced regionally for a set area or biome. This process is expensive; so while ideal, it is not yet used in practice; particularly in the tropics where it is likely needed most due to the loss of forests.

5.7. Time Horizon

Different profiles correspond to the release of GHG emissions from biofuels due to the establishment of crops, emissions from LUC, and potential reversion of crop lands to other activities after biofuel production. In the typical conversion of crop land to biofuels, the bulk of the LUC emissions happen in the first couple of years following conversion, and then decay slowly over decades to centuries. Thus, temporal release of GHG emissions is important to evaluate, although a finite baseline is difficult to predict.

In estimating the potential GHG reductions obtained by producing biofuels, it is important to consider the differing time profiles of emissions from biofuels and petroleum fuels. When iLUC is analyzed the analysis expands to two or more different land types to evaluate the time profile, (O'Hare, et al. 2009). These emissions represent an up-front cost of biofuels production that is different in nature to the ongoing emissions from the biofuels production cycle. For use in LCA, these emissions must be allocated to the functional unit (e.g., 1 MJ of biofuel). Figure 5.15 depicts the fundamental issue of timing and relationship between soil carbon aggregation and land-use timing.

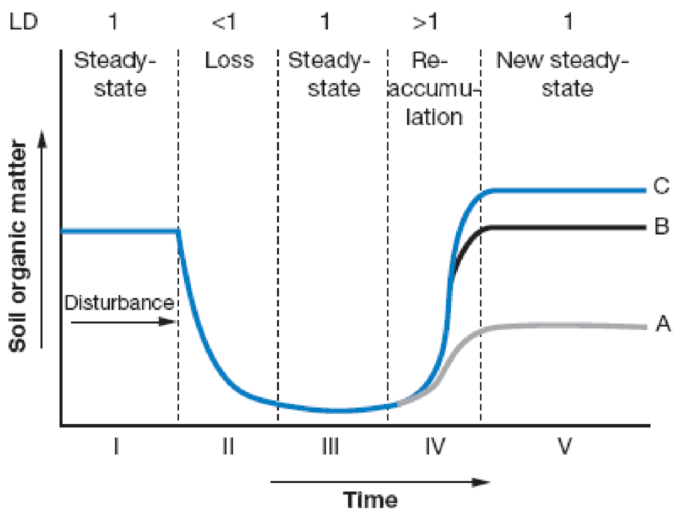

Figure 5.15. Schematic Showing Change in SOC Following Disturbance; Three New Land Use Practices Shown

The simplest approach to converting this CO_2 stock change to a per-MJ flow is to divide the iLUC emissions over a quantity of biofuels assumed to be associated with these emissions. No clear objective scientific method provides a basis for choosing this value; the EPA's RFS2, the Searchinger analysis, and the ARB analysis chose to assume 30 years of fuel production at current yields. One hundred year time horizons with discounted emissions were also examined. Both approaches present challenges. A long time horizon may capture the ongoing emissions from biofuels but presents the problems of shifting environmental burdens across generations to our grand children. Also, accounting for the GWP weighted emissions does not necessarily reflect the impact or cost of global warming.

Figure 5.16 demonstrates this concept based on output from the Btime model for gasoline and corn ethanol. This model takes into account the atmospheric fate of GHG species over time where CO_2 is reabsorbed (O'Hare, et al. 2009) by biomass and the oceans.

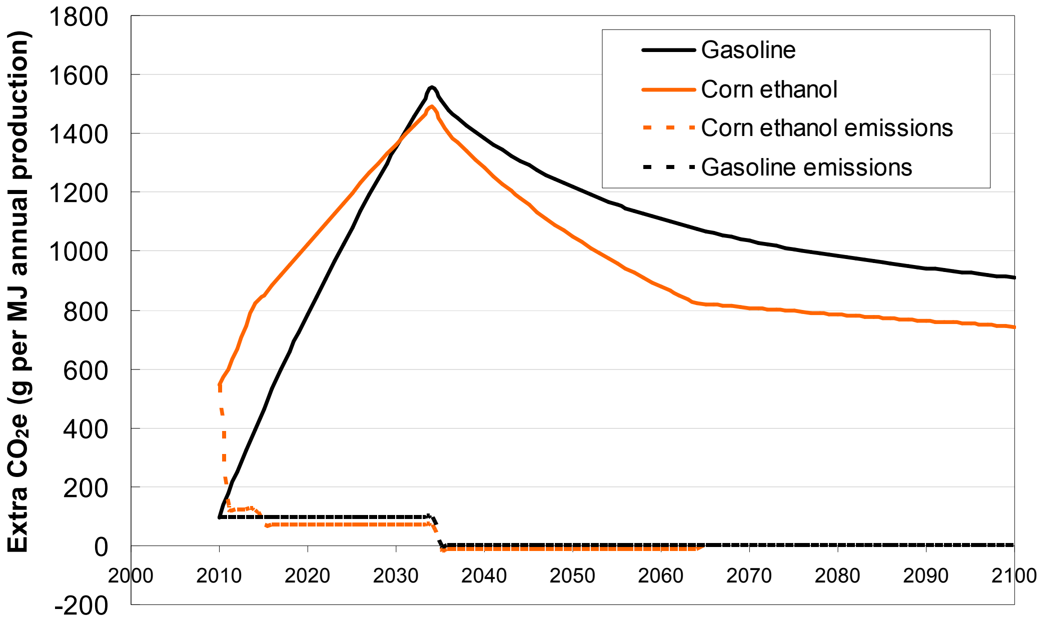

Figure 5.16. Cumulative GHG Emissions Based on Btime Model

First, properly accounting for the upfront emissions shows that these cause more warming *as measured at any fixed point in the future* than they would if spread out over time, as modeled using straight-line amortization (e.g., over 30 years). The use of a 30-year time horizon is arbitrary. Some biofuel projects may fail and revert to other uses more quickly. Other biofuel projects can persist for many decades. However, accounting for the uptake of CO_2 also presents challenges. If CO_2 is absorbed by the oceans, these impacts are not taken into account with an accounting of GWP.

Finally, there are several new approaches, including the time factor approach (Kendall et al., 2009). This approach is a correction factor for emissions timing for other applications, including manufacturing emissions for renewable energy technologies. The time factor approach would apply to biofuel timing as a shock value rather than amortized value, so the burden of emissions does not span over several successions of biofuel crops. This value is generally higher than the effect from amortized values.

5.8. Other Indirect Effects

The production and use of transportation fuels include a wide range of indirect activities that contribute to GHG emissions over their life cycle. Recent CLCA analyses for the RFS2 and LCFS have expanded the boundaries to include indirect effects associated with biofuel production, including iLUC discussed in Section 5 and the macro economic effects linked to iLUC analysis. However, a range of activities fall into the indirect emission category.

Indirect effects are inherently difficult to quantify. A working definition of indirect effects includes those related to either price-induced or behavioral changes in the marketplace. In the case of biofuels, iLUC is a price-induced indirect effect. Other indirect effects include those associated with the user of energy carriers, primarily natural gas, electric power, and natural gas for fertilizer production. Indirect effects are also associated with petroleum and natural gas-based energy systems. Life Cycle Associates examined many of the indirect effects associated with petroleum fuels for the New Fuels Alliance (Unnasch 2009). Some of the issues associated with petroleum and biofuels are addressed under the RFS2 analysis but many are not. For example, the RFS2 does not examine marginal fertilizer and chemical supplies, capacity constraints on electric power, or the international effects of fossil fuel use. Market induced indirect effects associated with energy use and change in resource mix could be calculated with the same general approach as indirect LUC. A report by the National Academy of Sciences concludes that attributing political events, such as the protection of oil supply to petroleum, is not feasible (NRC 2010).

Table 5.8 summarizes indirect effects associated with fuel production pathways. The magnitude of most indirect effects is estimated to be small and, therefore, many do not receive the same rigorous analytical attention as iLUC modeling. Nonetheless, for completeness, many of the indirect effects associated with fuel production require more attention.

Table 5.8. Indirect Effects Associated with Fuel Production

Effect	Analysis Tool	Comment
Crop land use Marginal Fertilizer inputs Co-product feed	FASOM/FAPRI, GTAP	Models estimate incremental land used for biofuel production. RFS2 analysis also predicts marginal fertilizer and associated N_2O while LCFS analysis uses average crop inputs. Supply/demand effects of co-products addressed through price elasticity or substitution of corn via DGS.
Take back/rebound effect Food price effects	FASOM/FAPRI, GTAP NEMS	Models use price elasticity response curves to estimate fuel and food usage. Increased biofuel usage should induce additional supply and increase in gasoline consumption, and results in food shifts. Biofuel shock, blend logistics, and other factors are modeled, but consistency among models and comparison of results remains an issue.
Non market price effects	Commodity trader expertise	Non equilibrium price spikes are not adequately addressed. Models all calculate long run economics. However, price spikes can result in long lasting economic dislocation, LUC, and other indirect effects.
Oil production and refining, petroleum co-products	Refinery and energy model	Petroleum co-products are treated through allocation with GREET and by use of an LP model for JEC. Neither approach fully addresses the GHG impact of all refinery products or the indirect effects on energy inputs.
Natural gas consumption	NEMS	EPA is using NEMS model to assess impacts on the energy system. The impact of natural gas use on other energy markets is estimated for RFS2 scenarios. NEMS is a U.S. energy model and does not reflect the global impact of energy markets. Inputs on power, fertilizer, and fuel production capacity are not transparently examined.
Fertilizer production	Energy/chemical market model, Historical trends	Natural gas is the leading source of nitrogen fertilizer but most of the growth in fertilizer has been with coal. The indirect effect of natural gas use on fertilizer is not adequately addressed by NEMS since the model addresses U.S. energy systems. The effect on natural gas capacity remains an issue.
Electric power generation	Electricity market model, historical trends, regulatory constraints	The issue of marginal electric power resources and the effect on energy systems depends on the outlook for power plant fuels and power plant capacity (how many new coal plants vs. nuclear, etc.). The assumptions on capacity growth and fuel LCA are not adequately addressed.

NEMS = EPA's National Energy Modeling System

6. Recommendations

Fuel LCA models and LCA studies aim to address the factors that affect the direct and indirect emissions associated with conventional petroleum fuels and biofuels. A number of issues associated with the models are identified in this report. Some fall into the category of execution issues that can readily be addressed by model developers. Other issues require more research in the areas of fuel cycle analysis, land use and indirect effects, or overall fuel LCA modeling. The following suggestions would improve the overall effort to address the subject. Areas of recommended research follow.

Execution Issues

Many fuel LCA models and studies could benefit from better documentation and transparency in calculations and reporting. In order to facilitate better transparency and an understanding of the results, LCA models and studies should:

- Provide current documentation of model inputs, assumptions, uncertainties, and results.
  - Publish integrated publications as well as peer reviewed articles.
- Provide disaggregated results for both fuels and intermediate products (ammonia for example).
  - Results by conversion step (e.g., corn farming, ethanol production, etc.)
  - Disaggregated WTT/fuel carbon, vehicle fuel efficiency and emissions, and WTW results
- Provide analysis for a calibration case for WTW and LUC analysis based on a simple biofuel configuration[45].
- Treat key performance parameters as exogenous to the fuel LCA model (vehicle fuel efficiency, emission factors, etc.).
- Validate and document the linkages between biorefinery operation and econometric data used to create sectors within agro economic modeling. Also provide a more transparent representation between energy sector physical data and economic data.

WTW Fuel Cycle Analysis Recommendations

- Perform life cycle analysis of LCA inputs, especially chemicals and fertilizers.
  - Agricultural chemicals (fertilizers, pesticides) should reflect the actual resource mix (natural gas, coal, electricity, etc.) used to produce fertilizers and pesticides.
  - Chemicals (acids, bases, catalysts, conditioning minerals, etc.) used in fuel plants or other steps in the fuel pathway have been mostly omitted from fuel pathway analyses so far, as they are not represented in the main fuel pathway models.
  - Upstream energy and emission burdens should be included in fuel cycle analysis, represented by the correct resource mix.
  - Most biofuel pathways underestimate fuel plant emissions because chemical production burdens are ignored.

[45] This recommendation may be difficult to implement as LCA studies often show a strong preference for a technology mix, allocation method, or other key assumption.

- Investigate the treatment of key parameters such as projections of yield, fertilizer application, and other inputs and linkages to LUC/indirect effect models.
- Develop a consistent method for the treatment of co-products with WTW calculations and LUC analysis as well as among co-product types including feed, electric power, and chemicals.
  - Address unintended consequences such as incentivizing lower biofuel yields.
  - Consistent method needed for regulation across all regions and fuel applications.
  - More flexible tools to assess feed, chemical, and energy co-products and their broader environmental impacts.
- Develop consistent presentation and reporting and demonstrate with various fuel LCA models[46].
  - Consistent documentation format for operating parameters (such as kWh/gal) and model inputs (J electric power/MJ product).
  - Consistent documentation for LCI data and interim calculation results.
  - Documentation must be sufficient to allow a third party to reproduce the results.
  - Develop a consistent approach for representing LCI data and integrate efforts with other, non fuel, LCA efforts.
  - Develop data base of LCI parameters that enables sharing of life cycle data among analysis tools, and supports structured database calculations.
- Review fuel LCA inputs and develop documented uncertainty analysis of WTW emissions, carbon stock factors, and factors driving land cover predictions.
  - Develop estimates of likely ranges of parameter values, their dependencies, and the shapes of the probability distribution functions that are tied to process inputs[47].
  - Conduct importance analysis to determine key parameters.
  - Assess the impact of asymmetrical environmental impacts.
  - Run stochastic simulations in uncertainty tool, such as Monte Carlo simulations, for limited set of input parameters to determine uncertainty.
  - Uncertainty analysis can be done with Oracle Crystal Ball software (or similar software) within an Excel ™ workbook either within the fuel LCA model or an off-model representation of various fuel pathways.

<u>Land Use Change and Other Indirect Effects</u>

- Harmonize (make consistent) LUC inputs and output formats among different models.
  - Preserve data on GHG species and other pollutants in address ranges in GWP.
  - Configure Winrock carbon stock factors for GTAP regions.
  - Develop a consistent approach to defining indirect effects and fuel blending logistics as applied to LUC and other models.
- Coordinate and integrate different models to capture all factors that affect land use, including treatment of time; care must be taken to ensure that models representing

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[46] Life cycle inventory data could readily be presented on a consistent functional unit (g N fertilizer, MJ fuel). The upstream fuel cycle, carbon in fuel, and combustion emissions should be presented per unit of energy output (MJ).
[47] Probability distributions should be based on measurable quantities such as electricity and natural gas usage rather than derivative values such as efficiency measure that lump different energy inputs.

different regional scales are appropriately integrated (such as integrating a global model with a U.S. model).

- Research price/yield response with data that are independent from price. Also examine models of agricultural inputs and yield that do not rely on econometric data
- Develop a model of the indirect impacts of biorefinery and conventional fuel use on the energy sector.
  - Inputs should be consistent with iLUC models or run on platforms such as GTAP.
  - Consider energy inputs to all primary fuel inputs including natural gas, fertilizer, oil refining and co-products, and electric power.
  - Consider realistic scenarios for capacity expansion and shifts in energy resources.
- Develop linkages between more detailed carbon stock and N_2O analysis and biofuel LUC models.
- Examine the effect of cropping systems on soil carbon storage and the relationship to LUC models.
- Develop an uncertainty analysis that captures all of the inputs to LUC, not just defined model parameters.
- Develop methods to validate components of LUC models.
  - Relate yield projects to historical performance.
  - Examine rate of land cover change, conversion of crops, cattle stock rates, deforestation, and other LUC parameters to model predictions.
  - Address the effect of price spikes and non-equilibrium price effects on land conversion and reversion.
- Develop a reduced form analysis that allows a broader user set to examine the effect of carbon stock factors, yield, biorefinery performance, and other factors that affect both iLUC and other indirect effects.
- Examine the causation between deforestation, land cover change, agriculture, and biofuels.

<u>Future of Model Development and Model Merging</u>

Ideally, LCA tools would cover a range of parameters including the process inputs and direct emission impacts, ability to assess marginal resources and economic impacts, land use impacts, co-products, agricultural, and energy markets. GHG impacts include gases other than CO_2, CH_4, and N_2O, as well as albedo, agricultural and forest feedback, water cycles, and other effects.

- Develop models that more seamlessly and transparently assess the relationship between economics, energy systems, land use change, and GHG emissions over time.
  - In executing such an analysis, sufficient soft links should be preserved to allow for comparison between models or inspection of model results. For example, the calculation of land cover area and carbon emission factors should be accessible in spreadsheet form so that users can examine these key intermediaries and perform sensitivity analyses.
- Develop relational database file structure for GREET, GHGenius, and LEM with spreadsheets-based user interface to allow for more transparent operation and file structure.

- Develop calibration case to compare fuel LCA, LUC, and integrated models on a defined set of biofuel scenarios and parameters such as yields, energy inputs, and co-product treatment.
- Develop a uniform model for nitrogen application/improvement, yield/improvements (via price or demand expansion and validated with physical performance data).
  - Address questions about N_2O production from nitrogen fixation.

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Appendix A. Life Cycle Data Tables

Table A.1. Life Cycle Data for Biodiesel Production

Model	U.S. Soybean Oil				JEC				GH Genius
Feedstock	CA-GREET 1.8b	GREET 1.8c.0	GREET 1.8d.1	EPA RFS2	Brazilian Soybeans	Malaysia Palm	EU Rapeseed	EU Sunflower	U.S. Soy
Ag Farming and Chemicals	28.52	30.94	24.36	-8.40	56.40	15.73	49.37	28.04	22.11
Ag Transport	2.76	3.02	2.92	2.58	35.88	1.16	0.30	0.28	3.10
Fuel Production	25.28	36.27	29.84	12.47	-14.81	36.14	-3.47	2.24	14.85
Co-product Credit	-41.96	-48.20	-49.46	0.00	-5.95	-5.95	-5.95	-5.95	-79.35
Fuel Transport	2.2	0.7	0.76	0.70	1.27	1.27	1.27	1.27	1.43
Vehicle/Fuel Emissions	4.45	0.78	0.78	0.66	0.80	0.80	0.80	0.80	0.80
Land Use	62.0	0.0	14.2	31.9	0.0	0.0	0.0	0.0	65.6
Net Emissions	83.3	23.5	23.4	39.9	73.6	49.2	42.3	26.7	28.5

Table A.2. Life Cycle Data for Renewable Diesel Production

Model	CA-GREET 1.8b	JEC			GH Genius
Feedstock	RD II, Soy (U.S.)	NExBtl RD II, Rapeseed (E.U.)	UOP RD II, Rapeseed (E.U.)	NExBtl RD II, Sunflower (E.U.)	CETC RD I, Canola
Ag Farming and Chemicals	27.47	48.70	42.85	27.65	27.12
Ag Transport	2.65	0.29	0.26	0.27	1.64
Fuel Production and co-product	-12.63	-7.29	0.11	-1.65	14.06
Fuel Transport	1.90	1.15	1.15	1.15	1.29
Vehicle Emissions	0.78	0.78	0.78	0.78	0.78
Land Use	62.0				
Net Emissions	82.2	43.6	45.2	28.2	44.9

Table A.3. Life Cycle Data for Cellulosic Ethanol Production

Model	GREET 1.8c			JEC		LEM		GHGenius	
Feedstock	Farmed Trees	Forest Residue	Switch Grass	Farmed Trees	Waste Wood	Farmed Trees	Switch Grass	Farmed Trees	Switch Grass
Biomass Production	4.40	7.89	16.37	6.28	0.95	13.68	14.53	6.55	8.35
Feedstock Transport	2.13	3.74	1.26	0.88	3.19	4.01	2.64	0.78	2.22
Fuel Prod. and Co-Prod. Credit	-5.92	6.58	-2.07	13.33	13.33	12.14	5.28	-0.92	3.59
Fuel Transport	1.44	1.45	1.44	1.54	1.54	2.38	1.98	1.73	1.73
Vehicle CH_4, N_2O	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Net Emissions	2.9	20.5	17.8	22.8	19.8	33.0	25.2	8.9	16.7

Table A.4. Life Cycle Data for Sugarcane Ethanol Production

Model	CA-GREET 1.8b			EPA RFS2	JEC	
Feedstock	Base Case	Case 1:Mech. Harv., Co-gen	Case 2:Co-gen	Base Case	Base Case	Co-Product
Feedstock Production	19.00	11.00	19.00	38.37	14.45	14.45
Feedstock Transport	2.00	2.00	2.00	2.23	0.85	0.85
Fuel Prod. and Co-Prod. Credit	2.10	-4.90	-4.90	-1.82	0.73	-10.31
Fuel Transport	3.50	3.50	3.50	2.23	7.69	7.69
Vehicle CH_4, N_2O	0.80	0.80	0.80	0.83	0.80	0.80
Land Use	46	46	46	4.08		
Total	73.40	58.40	66.40	45.92	24.52	13.48

Table A 5. Life Cycle Data for Corn and Wheat Ethanol Production

Feedstock	Dry Mill Corn				Wheat	LEM	GH	BESS
Model	CA-GREET 1.8b	GREET 1.8c.0	GREET 1.8d.1	EPA RFS2	JEC	DM Corn	DM Corn	DM Corn
Feedstock Production	35.85	34.93	34.84	41.93	39.38	26.56	13.23	26.19
Feedstock Transport	2.22	2.16	2.16	4.04	0.63	3.36	1.58	2.11
Fuel Production	38.30	27.33	27.25	30.68	19.66	45.65	12.27	12.30
Co-product Credit	-11.51	-14.52	-10.73	0.00	0.00	-22.59	0.00	
Fuel Transport	2.70	1.44	1.43	0.00	1.54	1.81	1.73	1.40
Vehicle CH_4, N_2O	0.80	0.80	0.80	0.83	0.80	0.80	0.80	0.00
Land Use	30.00	0.86	14.24	0	0	28.05	9.89	0
Total	98.4	53.0	77.2	77.5	62.0	83.6	39.5	42.0

Table A.6. Life Cycle Data for Hydrogen

Study	CA-GREET 1.8b		JEC			LEM	GH Genius
Feedstock	NA NG, Central LH_2 Delivery	NA NG, Onsite	Siberian NG, Onsite	EU NG, Onsite	Siberian NG, Central	NA NG, Central	NA NG, Onsite
Feedstock Extraction & Processing	8.2	8.2	5.7	4.9	5.2	9.6	10.5
Feedstock Transport	NA	NA	22.1	2.8	20.1	4.0	3.0
Feedstock Distribution	NA	NA	0.8	0.9	0.9	NA	NA
Fuel Production	80.9	80.9	84.7	86.6	74.1	67.2	68.9
Liquefaction	43.4	NA	NA	NA	NA	NA	NA
Distribution, Storage & Compression	9.75	9.1	10	10	9.1	15.6	20.2
Total	142.3	98.2	123.3	105.2	109.4	96.4	102.6

Table A.7. Life Cycle Data for Petroleum Fuels

Feedstock	Crude Oil to CARBOB			Crude Oil to Gasoline	
Study	GREET 1.8d.1	GREET 1.8c.0	CA-GREET 1.8b	JEC	GHGenius
Oil Total					
Oil Production	2.6	3.0	6.8	3.6	7
Upgrading					
Venting	1.7	2.4	0.7		1
Flaring	0.7	0.7	0.9		0.5
Upstream Fuel Cycle, Co-products					
Oil Transport	0.5	0.8	1.4	0.9	1
Refining, RFG	10.3	12.43	11.5	7	12
Transport & Delivery	0.5	0.5	0.5	1	1
Fuel Carbon, RFG	72.8	73	73	72.8	73
Vehicle CH_4, N_2O, SI LDV	0.8	0.8	0.8	0.8	0.8
Total	89.8	93.6	95.6	86.1	96.3

Table A.7. Life Cycle Data for Petroleum Fuels (Continued)

Feedstock	Crude Oil to Gasoline			Diesel	Oil Sands	
Study	NETL	Jacobs	EPA RFS2	BESS	GREET 1.8c.0	Jacobs
Oil Total			18.2	10.78		
Oil Production	6.9	4.2			12	14.2
Upgrading					8	8.3
Venting		0.4			1	0
Flaring		0.4			1	0
Upstream Fuel Cycle, Co-products		3.8				5.9
Oil Transport	1.4	2.8			1	0.94
Refining, RFG	9.3	12.5			12	12.6
Transport & Delivery	1.0	0.42			1	0.42
Fuel Carbon, RFG	71.8	72.9	74.0	73	73	72.9
Vehicle CH_4, N_2O, SI LDV	0.8	0.8	0.8		0.8	0.8
Total	91.2	98.2	93.1	93.1	109.8	116.1

Table A.8. Life Cycle Data for Natural Gas

Study	CA-GREET 1.8b	JEC		LEM	GHGenius
Feedstock	North America NG	Siberian NG	EU NG	US NG	US NG
Extraction & Processing	7.2	3.8	3.3	8.6	6.2
Transport	0.485	15.0	1.9	0.0	0.0
Distribution	0.485	0.6	0.6	3.3	1.9
Compression	2.14	2.9	2.9	4.0	4.0
Vehicle Emissions & Fuel	57.7	57.7	57.7	49.1	49.1
Total	68.0	80.0	66.4	65.1	61.3

Table A.9. Life Cycle Data for Electricity Generation

Study	CA-GREET 1.8b			GREET 1.8c.0		
Feedstock	CA Marginal	CA Average	Coal	U.S. Average	NG CCGT	Coal
Feedstock Extraction & Processing	11.36	10.57	12.25	17.27	23.96	20.26
Feedstock Transport	1.54	1.43	1.65	2.33	3.24	2.75
Feedstock Distribution	0	0	NA	0	0	NA
Power generation	92.1	112.2	292.3	197.6	117.6	329.9
Electricity Distribution	0	0	0	0	0	0
Total	105.0	124.2	306.2	217.2	144.8	352.9

Table A.9. Life Cycle Data for Electricity Generation (Continued)

Study	GREET 1.8c.0		JEC			
Feedstock	Biomass	Nuclear	Siberian NG; CCGT	Waste wood; CCGT	Coal	Nuclear
Feedstock Extraction & Processing	0	4.05	7.2	0.8	38.1	4.07
Feedstock Transport	0	0.55	28.1	3	NA	NA
Feedstock Distribution	NA	NA	1.1	NA	NA	NA
Power generation	10.8	0	104.6	1.4	207	0.3
Electricity Distribution	0	0	0	0	0	0
Total	10.8	4.6	141.0	5.2	245.1	4.4

Table A.10. EPA RFS2 Results (Compared to Gasoline)

Emission Category	**2005 Gasoline Baseline**	**Sugar Cane, No Trash, Marginal Power**	**Switchgrass Biochemical**	**Switchgrass Thermo-chemical**	**Corn Stover, Biochemical**	**Corn Stover, Thermo-chemical**	**Corn, Base Dry Mill NG**	**Corn, Dry Mill, Fractionation, CHP**	**Corn, Wet Mill NG**	**Corn, Dry Mill Biomass**	**Sugar Cane, No Trash, Marginal Power, CBI**	**Sugar Cane, No Trash, Avg. Power, CBI**
Domestic Livestock		0	3462	3623	9086	9511	-3746	-3746	-3746	-3746	0	0
Domestic Farm Inputs and Fertilizer N2O		0	4,217	4,414	1,660	1,737	8,281	8,281	8,281	8,281	0	0
Domestic Rice Methane		0	-1,555	-1,628	434	455	-209	-209	-209	-209	0	0
Tailpipe	79,004	880	880	880	880	880	880	880	880	880	880	880
International Rice Methane		485	-920	-963	0	0	2,089	2,089	2,089	2,089	485	485
International Livestock		-128	-245	-257	0	0	3,458	3,458	3,458	3,458	-128	-128
Domestic Soil Carbon		1,049	-2,487	-2,654	-10,820	-11,355	-4,033	-4,033	-4,033	-4,033	1,049	1,049
Fuel and feedstock transport		4,637	2,808	2,939	2,418	2,531	4,265	4,265	4,265	4,265	4,637	4,637
International Farm Inputs and Fertilizer N2O		37,884	1,310	1,371	0	0	6,601	6,601	6,601	6,601	37,884	37,884
International Land Use Change		4,300	15,073	15,776	0	0	31,797	31,797	31,797	31,797	4,300	4,300
Fuel Production	19,200	-11,027	-32,628	3,737	-32,628	3,737	32,369	27,702	41,461	9,437	-11,027	687
Net Emissions	98,204	38,080	-10,087	27,238	-28,969	7,495	81,751	77,083	90,842	58,819	38,080	49,795

Table A.11. EPA RFS2 Results (Compared to Diesel)

Emission Category	2005 Diesel Baseline	Soy Biodiesel, base yield	Waste Grease, Soy Biodiesel	Switchgrass, F-T Diesel	Corn Stover, F-T Diesel
Domestic Livestock	0	-2,100	0	3,590	9,422
Domestic Farm Inputs and Fertilize	0	106	0	4,373	1,721
Domestic Rice Methane	0	-7,950	0	-1,613	450
Tailpipe	79,008	700	1,006	700	700
International Rice Methane	0	2,180	0	-954	0
International Livestock	0	-6,436	0	-254	0
Domestic Soil Carbon	0	-8,896	0	-2,555	-11,240
Fuel and feedstock transport	0	3,461	4,972	2,911	2,507
International Farm Inputs and Fertil	0	5,402	0	1,358	0
International Land Use Change	0	42,543	0	15,630	0
Fuel Production	17,998	13,153	13,788	5,391	5,391
Net Emissions	97,006	42,161	19,766	28,576	8,952

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